



**STABILITY AND RHEOLOGICAL PROPERTIES OF OIL-IN-WATER EMULSIONS
STABILISED WITH PROTEIN ISOLATES FROM BROWN BAMBARA GROUNDNUT**

By

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ABSTRACT

An emulsion is a mixture of two immiscible liquids which are held together by agents called emulsifiers. Food products such as mayonnaise, salad dressings, creams, sauces and milk are examples of oil-in-water (O/W) emulsions. Due to a high demand of healthy products, food developers are producing products with nutritional benefits. Protein added into food serves as an enhanced nutrient source. Though some food products comprise of protein, it comes mainly from animal sources which can be detrimental to the human body due to their high cholesterol levels. Vegetable proteins from legumes such as soy, lupin, pea, faba bean and lentil have shown to have the potential of being emulsifiers in O/W emulsions. Bambara groundnut (BGN) is a legume with a high protein content and is available in Africa however it is underutilised. It is underutilised since there is insufficient knowledge about its functionality in food emulsions. The potential of BGN flour and starch has been studied in O/W emulsions and illustrated their ability to serve as emulsifiers. Due to insufficient work done on the use of BGN protein as an emulsifier in O/W emulsions, this study aimed to determine its effect on the stability and rheological properties of the O/W emulsions. Protein was extracted using isoelectric precipitation method. O/W emulsions were formulated by homogenising the protein solution with oil at 20 000 rpm for 5 minutes using a D-lab homogeniser. A Zeiss Axio light microscope was used to capture the images of the O/W emulsions. A turbiscan MA 2000 was used to determine the stability of the O/W emulsions over a period of 5 hours. A Discovery Hybrid rheometer was used to perform both rotational and oscillatory tests on the O/W emulsions. Design-expert version 10 was used to determine the different emulsion compositions. A mixture design was used comprising 6 to 15% protein content, 33.25 to 39% oil content and 55 to 60% water content and 14 compositions were established. The protein extracted had a yield of 16.6%. The low protein emulsions with 6% protein content were unstable after 2 hours, the medium protein emulsions with 8.14 to 10.50% protein content were stable for 12 hours and the high protein emulsions with 12.53 to 15% protein content were still stable after four weeks except for the emulsion with 12.78% protein content which was still stable after three weeks. The stability and instability phenomena were illustrated using turbiscan backscattering profiles. The low protein emulsions demonstrated phase separation (indicated by a thick vertical portion of the backscattering profile) and coalescence (indicated by a thick horizontal portion of the backscattering profile). The stable emulsions had no variation in the backscattering profile. All emulsions regardless of composition exhibited shear thinning. For the oscillatory rheological tests, the amplitude, frequency, temperature and time sweep tests were conducted. The amplitude tests were conducted to determine the storage and loss modulus and the linear viscoelastic region (LVR) of the emulsions. All emulsions were viscoelastic with the high

protein emulsions having higher moduli than the low protein emulsions. All the emulsions had a LVR at lower strains illustrating stability at such conditions. All emulsions had a point where the storage and loss modulus were equal except for some of the low protein emulsions which had no crossing. All emulsions demonstrated weak gel properties. All emulsions were still in their LVR at a strain of 0.2% except for emulsion 3 (6% protein, 36.26% oil, 57.74% water) which was linear at a lower strain. This strain was therefore used to conduct the frequency, temperature and oscillatory time tests. The frequency had an effect on all emulsions. As the frequency increased both the storage and loss modulus increased. A temperature range of 5 to 40°C was used to determine the effect of refrigeration, cold and room temperature on emulsions. The emulsions were more elastic and stable at refrigeration than at cold to room temperature. As all emulsions were tested immediately after homogenisation, the oscillatory time test showed that they had not stabilised completely during the first hour as both the storage and loss modulus increased indicating that energy gained from mixing was still present in emulsions either to enhance bond formation or energy that was dissipated in the system respectively. A correlation was able to be drawn from the different techniques used to describe the quality of the emulsions. Variation in backscattering intensity demonstrated that the low protein emulsions were unstable and from visual observation, they were liquid-like, with the least viscosity. The low protein emulsions had lower moduli than the high protein emulsions. From visual observation, high protein emulsions were thick and rheological information supported this by their viscosity being high. The high protein emulsions had droplet sizes which were more uniform and dispersed than the low protein emulsions. The difference in composition had an effect on both the stability and rheological properties of the O/W emulsions. Therefore, BGN protein from brown seeds had emulsifying and thickening properties and can therefore serve as an emulsifier in food O/W emulsions.

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DEDICATION

I dedicate this thesis to JEHOVAH. As long as I live, You will always be my GOD.

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GLOSSARY

Symbol	Description and unit
BGN	Bambara groundnut
BGNF	Bambara groundnut flour
BBGN	Brown bambara groundnut
LPE	Low protein emulsion
MPE	Medium protein emulsion
HPE	High protein emulsion
O/W	Oil-in-water
W/O	Water-in-oil
W/O/W	Water-in-oil-in-water
O/W/O	Oil-in-water-oil
HLB	Hydrophilic-lipophilic balance
PGFA	Polyglycerol Esters of Fatty acids
SMG	Succinic Acid
SSL	Sodium stearoyl lactylate
CSL	Calcium stearoyl lactylate
CITREM	Citric Acid
NaOH	Sodium Hydroxide
HCL	Hydrochloric acid
PC	Phosphatidylcholine
PE	Phosphatidylethanolamine
ESI	Emulsion stability index (%)
EAI	Emulsion activity index

TSI	Turbiscan stability index
LVR	Viscoelastic region
XG	Xanthan gum
PGA	Propylene glycol alginate
CMC	carboxymethyl cellulose
NaCN	Sodium caseinate
SAOS	Small amplitude oscillatory shear
LAOS	Large amplitude oscillatory shear
R ²	R-square
SSE	Sum of square error
RMSE	Root mean square error
ANOVA	Analysis of Variance
rpm	revolution per minute
G'	Storage modulus (Pa)
G''	Loss modulus (Pa)
ω	Angular frequency (Rad/s)
μm	micrometer
w/v	weight per volume
°C	Degree Celsius
s	second
v	Creaming velocity
g	Gravitational acceleration
ρ	density
r	radius
X _i	Average backscattering for each interval of measurement

X_{BS}	Average of X_i
n_t	number of scanning (turbiscan measurement)
V_e	Volume of the emulsion
V_w	Volume of the separated bottom layer
V	Volume of the dispersed phase (for EAI equation)
R	Radius of oil droplets (for EAI equation)
m	Mass of emulsifier (for EAI equation)
δ	Phase angle ($^\circ$)
τ	Stress (Pa)
η	Viscosity (Pa.s)
K	consistency coefficient (Pa.s ⁿ)
$\dot{\gamma}$	Shear rate s ⁻¹
N	Flow behaviour index (dimensionless)
τ_0	yield stress (Pa)
τ_0^B	Bingham yield stress (Pa)
η^B	Bingham viscosity (Pa.s)
τ_0^C	Casson yield stress (Pa)
η^C	Casson viscosity (Pa.s).
τ	Shear stress (Pa)
τ_{max}	Initial shear stress
τ_e	Equilibrium shear stress
t	time of shearing (s)
k	kinetic constant
A	Initial stress (Weltman model) (Pa)
B	Time coefficient (Weltman model)

τ_e	Equilibrium shear stress
P	Initial shear stress (Hahn model) (Pa),
α	Sample's structural breakdown (s^{-1})

CHAPTER ONE

INTRODUCTION

1.1 Background

Emulsions are of great importance because they are the basis of most products. An emulsion is a mixture of two immiscible liquids with emulsifiers as agents keeping the mixture stable (Khan et al., 2011). The cosmetic, pharmaceutical, petroleum, chemical and agricultural products comprise of different emulsions (Deguchi and Ifuku, 2013) such as lotions, medicine, paint and insecticides. These emulsions can either be oil-in-water (O/W) emulsions or water-in-oil (W/O) emulsions (Prichapan and Klinkesorn, 2014).

The food industry comprises of several products in the form of emulsions (Rybak, 2013). Food analysis is performed on the raw materials, to processing of these materials until the final products in order to ensure the quality of food. Analysis of food describes its physical, chemical and sensory properties. Customers seek food of high quality, nutrition and value. Food scientists, therefore, need to develop food to meet the customers' requirements and analytical methods are used to obtain such products (Nielsen, 2014). For food quality control, rheological properties (Heldman and Lund, 2006) and stability characteristics of food can be used (Frankel, 2014). Food stability indicates how long food can remain unchanged (Traynor et al., 2013) and can, therefore, describe the shelf life of food products (Decker et al., 2010). Rheology, on the other hand, describes the flow or deformation characteristics of a sample under applied external force (Prasad et al., 2007).

Salad dressings, sauces, creams and milk are forms of O/W emulsions (Lam and Nickerson, 2013) in the food industry. Most of these emulsions exhibit a pseudoplastic flow behaviour and several studies have been conducted on food emulsions demonstrating this phenomenon. From the study of the rheological characterisation of salad dressings with lentil flours, Ma et al. (2013) reported that the salad dressing showed yield stress, pseudoplastic and more elastic than viscous. The thermal processing of lentil flour showed an increase in the stability of the salad dressing (Ma et al., 2013). A pseudoplastic behaviour was also present in salad dressing stabilised with xanthan gum (XG), propylene glycol alginate (PGA) and carboxymethyl cellulose (CMC) and was stable for four months (Fonseca et al., 2009). Mayonnaise exhibits a pseudoplastic behaviour when stabilised with XG and the increased oil content and XG concentration increased the yield stress and elastic modulus of the mayonnaise (Ma and Barbosa-Cánovas, 1995). Peressini et al. (1998) compared the rheological properties of traditional and light mayonnaise and reported that light

mayonnaise had a lower storage modulus and yield stress which supported the study conducted by Ma and Barbosa-Canovas (1995).

The design of dairy processes (production of cheese, yoghurt and cream) also relies on the rheological Newtonian behaviour of milk since it is composed mainly of water. Components of milk, such as fat affect the viscosity of milk. The decrease in temperature of milk increases the viscosity of milk. Milk can change from Newtonian to non-Newtonian when the concentration of the solids increases to a certain level (Norton et al., 2011). Velez- Ruiz and Barbosa- Canovas (1998) also confirmed this theory when milk became non-Newtonian at a solid concentration of more than 22.3%. Milk contains protein which serves as an emulsifier in dairy food products. Both whey protein and milk protein such as sodium caseinate (NaCN) have excellent emulsifying properties hence, it was of good interest to investigate the properties of creams with whey protein and NaCN. Research showed that whipping cream containing NaCN and whey protein exhibited pseudoplastic behaviour with yield stress (Long et al., 2016). The study conducted by Donkor et al. (2007) showed that yoghurt made by soy milk prepared with a combination of yoghurt cultures and probiotic cultures showed pseudoplastic behaviour as well.

There is a high demand for food containing vegetable proteins instead of animal proteins. Vegetable proteins are suitable to be utilized as emulsifiers because of their ability to reduce interfacial tension that occur between hydrophobic and hydrophilic molecules and because of their ability to unfold. In order to form a gel, protein needs to unfold to allow functional groups to be exposed — the unfolding of protein occurs by thermal denaturation (Batista et al., 2005). Vegetable proteins in food reduce cholesterol, and they can be controlled at high temperatures (Riscardo et al., 2003). Vegetable proteins such as faba bean, pea, soy, tomato seed, white lupin all emulsify O/W emulsions (Nikzade et al., 2012). Plant protein is still underutilized in the food industry because of incomplete information on their structure and functionality in food products (Johnston et al., 2015; Mafongoya and Ajayi, 2017). Bambara groundnut (BGN) is an underutilised legume, yet the third most important legume in semi-arid Africa (Ibrahim et al., 2018). There is insufficient knowledge of its protein in effecting the stability and rheological properties in food systems. A pool of BGN seeds that was used for this study comprised of 31.2, 26.0, 17.9 and 25.0% of the brown, red, cream (black eye) and cream (grey eye) coloured seeds respectively. The brown BGN seeds were chosen for this study as they had the highest quantity in the pool of BGN seeds.

1.2 Statement of Research Problem

Vegetable proteins have been proven to be able to stabilise emulsions, which can, therefore, serve as a replacement for animal-based products. Félix et al. (2019), Ma et al. (2013) and Nikovska (2012) demonstrated the ability of legumes in stabilising O/W emulsions. These studies also described the rheological properties of the O/W emulsions. Ma et al. (2013) and Nikovska (2012) described their pseudoplastic behaviour, while Félix et al. (2019) described their viscoelastic properties. Eltayeb et al. (2011) and Adeleke et al. (2018) studied the functionality of BGN flour including water and oil absorption capacities. Gabriel et al. (2013) investigated the emulsifying properties of Bambara groundnut flour (BGNF) and starch in an O/W emulsion over five days. The study showed that BGNF stabilised emulsions were more stable than the BGN starch stabilised emulsions. A study conducted by Adeyi et al. (2014) indicated that emulsions stabilised by BGNF exhibited shear thinning. Increasing the BGNF and oil concentration increased the apparent viscosity and the yield. Adebanke et al. (2017) and Brough et al. (1993) demonstrated the usefulness of BGN in the production of yoghurt and milk, respectively. However, there is insufficient knowledge of the potential of BGN protein isolates from brown seeds and its effect on the stability and rheological characteristics of O/W emulsions. Therefore, it is important to investigate the stability and rheological properties of O/W emulsions stabilised by protein isolate extracted from brown BGN.

1.3 Broad Objectives

The objective of this study was to describe the effect of brown bambara groundnut (BBGN) protein isolate on the stability and rheological characteristics of oil-in-water emulsions.

1.3.1 Specific objectives

The specific objectives of this study were to:

- (a) Extract protein isolates from BBGN.
- (b) Determine amino acid profile of BBGN protein isolate.
- (c) Determine the stability characteristics of the O/W emulsions stabilised with BBGN protein isolate.
- (d) Determine the flow and viscoelastic behaviour of O/W emulsions stabilised with BBGN protein isolate.

1.4 Research Hypotheses

This study hypothesised that:

- (a) BBGN protein isolates comprise of the essential amino acids.
- (b) BBGN protein isolates can stabilise O/W emulsions.

(c) O/W emulsions stabilised with BBGN protein isolate has shear thinning and viscoelastic properties.

1.5 Significance of the Research

New knowledge about the potential of BBGN protein isolates may be applied in subsistence farming which may contribute to zero hunger in poverty-stricken countries by providing a cheap source of protein and thus reducing malnutrition. BBGN protein isolate may be applied in food industries in the creation of more nutritious products meaning more jobs for both male and female resulting in gender equality. This new knowledge may also serve as a reference in which more future knowledge can be built upon regarding the use of BBGN protein in O/W emulsions. The BBGN protein may serve as a replacement for protein obtained from animal sources.

1.6 Expected Outcomes

The expected outcome of this study is to provide additional knowledge about BGN protein isolates from brown seeds that will serve as a solution to some nutritional and food production challenges. The knowledge is expected to provide food product developers with information on the functionality of BGN protein in O/W emulsions. As BGN is an underutilised crop, this study expects to use the new knowledge to appeal to the agricultural sector and to encourage both subsistence and commercial farmers to grow more of this crop. One journal article is expected to be published in an accredited Journal. The outcome of this investigation is expected to be presented in a national or international conference.

1.7 Delineation of the study

Protein was extracted from the brown coloured BGN flour; however, no modification was conducted. The protein isolate was obtained using isoelectric precipitation method.

1.8 Key words

Bambara groundnut, emulsion, emulsifier, protein, stability, shear rate, shear stress, viscosity, storage modulus, loss modulus

1.9 Thesis Overview

A study on the stability and the rheological properties of O/W emulsions emulsified with BBGN protein isolate is presented in this thesis. There are five chapters.

Chapter one introduces the previous work done on the stability and rheological properties of O/W emulsions stabilised by different legume proteins and establishes the missing gap which became the focus of this study, describes the objectives, hypothesis, significance, expected outcomes and the delineation of this study.

Chapter two describes the use of protein isolates from various legumes and their effectiveness in stabilising O/W emulsions. Studies on the use of BGN flour in O/W as well as a lack of studies on the use of BGN protein from brown seeds as an emulsifier in O/W emulsions are discussed.

Chapter three describes the materials and equipment used to conduct the investigation. The methodology including the stability (turbiscan) tests, rheological (rotational and oscillatory) tests, visual observation and capturing the images of the O/W emulsions was described in this section.

Chapter four presents the stability and rheology results which illustrates the behaviour of BBGN protein isolates. Previous studies are referenced in the discussion.

Chapter five concludes the investigation by highlighting the main outcomes and provides recommendations for further studies.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

As this study is focusing on the investigation of the use of BGN protein as an emulsifier, this section describes the characteristics of this legume, such as its nutritional composition and uses. The importance of emulsion stability, sensory and textural properties in food products are taken into consideration by food developers in order to satisfy the customers' requirements. Also discussed are different mechanisms of emulsion instability, and different models that illustrate rheology through deformation and flow behaviours.

2.2 Overview of Legumes in Human Nutrition

The word legume derived from the Latin word 'Legere' that means to gather. Legumes are part of the Fabaceae family, consisting of approximately 18 000 species (Chibarabada et al., 2017). They are plants which bear pods in which seeds grow (Akporhonor et al., 2006). Legumes contain nutrients that are required by human beings. They decrease cholesterol and can reduce glucose concentration in blood (Gepts et al., 2005). Amongst the legume species, some legumes are more vital compared to others with regards to socioeconomic value, production and consumption. Minor legumes are also called future legumes, promising legumes, neglected or underutilised (Chibarabada et al., 2017). Legumes also contain antinutritional factors that may be reduced or eliminated, for example, through soaking or thermal processes (Osunbitan et al., 2015). The legumes chickpea, cowpea, dry bean, groundnut, pigeon pea and soybean constitute 90% of the legume production. The remaining 10% includes BGN, faba bean, common pea, lablab, lentil and others. Most of these legumes can survive in dry conditions. The usual legume processes include dehusking followed by soaking, fermenting and cooking. Legumes residuals may also be used as livestock feed (Chibarabada et al., 2017). In developing countries, legumes serve as a source of cheap protein (Osunbitan et al., 2015). Table 2.1 illustrates the approximate composition of different legumes where all the legumes have a considerable amount of carbohydrates (30.16 to 79.01%) and protein (18.03 to 42.4%) ranging from and respectively. The amount of fat for all legumes described in Table 2.1 is low except for groundnut, soybean and lupin.

Table 2.1 **Composition of different legumes**

Legume	Proximate (%)										
	^d Dry										
	^a Bambara groundnut		^b Chickpea	^c Cowpea	Bean/ Bean	^e Faba Bean	^f Groundnut	^g Lentil	^d Lupin	^f Mung Bean	^c Pigeon Pea
Carbohydrate	57.16	60.45	56.60	59.2	59.87	79.01	58.95	38.0	65.12	56.63	30.16
Protein	18.03	22.48	24.13	31.1	30.57	29.12	27.30	42.4	21.9	24.46	36.49
Fat	6.05	2.38	4.37	2.0	3.22	42.60	2.23	11.1	1.40	4.78	19.94
Fibre	3.91	22.56	0.97	3.6	2.73	2.70	14.91	4.5	3.80	1.10	9.3
Ash	4.18	3.42	4.73	4.2	3.61	2.51	3.53	4.0	3.42	4.58	2.91

^aAdegunwa et al., (2014), ^bBhatt et al., (2015), ^c Olalekan et al., (2010), ^d El- Adawy et al., (2000), ^e Mortuza et al., (2009), ^f Khavita and Parimalavalli, (2014) and ^gKohajdová et al., (2013)

Figure 2.1 illustrates the different legumes. Chickpea is an annual crop (Man et al., 2015). There are two kinds of chickpea: *Desi*, made of a thick coloured seed coat and *Kabuli* which has a thin white or beige seed coat. *Desi* chickpea constitutes 80-85% of the chickpea production and is commonly grown in Asia and Africa while *Kabuli* chickpea grows in West Africa, North America and Europe. Like lentil, chickpea is cholesterol free (Jukanti et al., 2012).

Cowpea is regarded as a vital legume in most parts of the world (Khalid and Elhardallou, 2016). Africa produces 83% of the world's cowpea. Nigeria is the primary producer of cowpea in Africa contributing 45% to the global cowpea production (Boukar et al., 2016) and the second cowpea consumer in the world (Agbogidi and Egho, 2012). Cowpea has calcium and iron that exceed those found in food such as meat, fish and eggs (Agbogidi and Egho, 2012). Cowpea is also known as asparagus beans, black-eye pea, coupe, frijole, lubia, southern pea, sitao and yard-long beans (Nweke, 1988).

Dry bean originates from Latin America. Besides Antarctica, the dry bean is grown in all continents (Fageria et al., 2010). Though it requires more time to cook, it is regarded as one of the major pulse crops (Wiesinger et al., 2016). Dry bean is also called common bean, field bean, French bean, navy bean, pinto bean and snap bean (Fageria et al., 2010).

Faba bean is also known as the broad bean, horse bean and field bean (Boukhanouf et al., 2016). It is mostly produced in China and Ethiopia and comes in fourth regarding production after chickpea, pea and lentil (Ocana et al., 2015). The intake of faba bean has shown promise to manage diabetes, hypertension and prevents heart diseases (Turco et al., 2016).

Groundnut (peanut) is a globally important oil crop (Akram et al., 2018). It originates from South America, but also produced in Africa, North America and Asia (Idoko and Sabo, 2014). Groundnut is also referred to as cashew nut, monkey nut, peanut and wonder nut (Jain et al., 2016). Its oil is considered to be healthy as it contains monosaturated fatty acids (Olatunde et al., 2014).

Lentils are among the healthiest foods in the world. Lentils are cholesterol free. They have more fibres and antioxidants but have low sugar and saturated fat content. Lentils can be red or green with the red lentils containing more protein and antioxidants than the green lentils. Lentils cook quickly compared to other legumes (Kumar et al., 2016).

Lupin is non-starchy and a cheap legume, used in food such as bread, pasta and noodles. Its protein contains emulsion and foam forming characteristics vital in food development (Khan et al., 2015).

Mung bean originated from India (Kim et al., 2015). It is also referred to as moong, green gram, golden gram, chickasaw pea, oregon pea and chop suey bean (Nair et al., 2013). It takes 55-70 days to grow. Mung bean contains low oil content (Nair et al., 2013) but provides a cheap source of carbohydrates (Kim et al., 2015).

Pigeon pea, also known as red gram originated from India (Saxena et al., 2010). It contributes 5% of global production. Pigeon pea, soybean and mung bean are part of the same subtribe Phaseoleae. Pigeon pea tolerates extreme drought conditions better than many legumes (Odeny, 2007).

Globally there is an increase in soybean production. Soybean earns more commercial interest for its oil and protein. It is the second largest vegetable oil source in the world. In China, soy is one of the most crucial plants derived foods amongst barley, milk, rice and wheat (He and Chen, 2013). Globally, the US and Brazil are the first and second soybean producers, respectively with Egypt as the leading producer in Africa (Lokuruka, 2010).

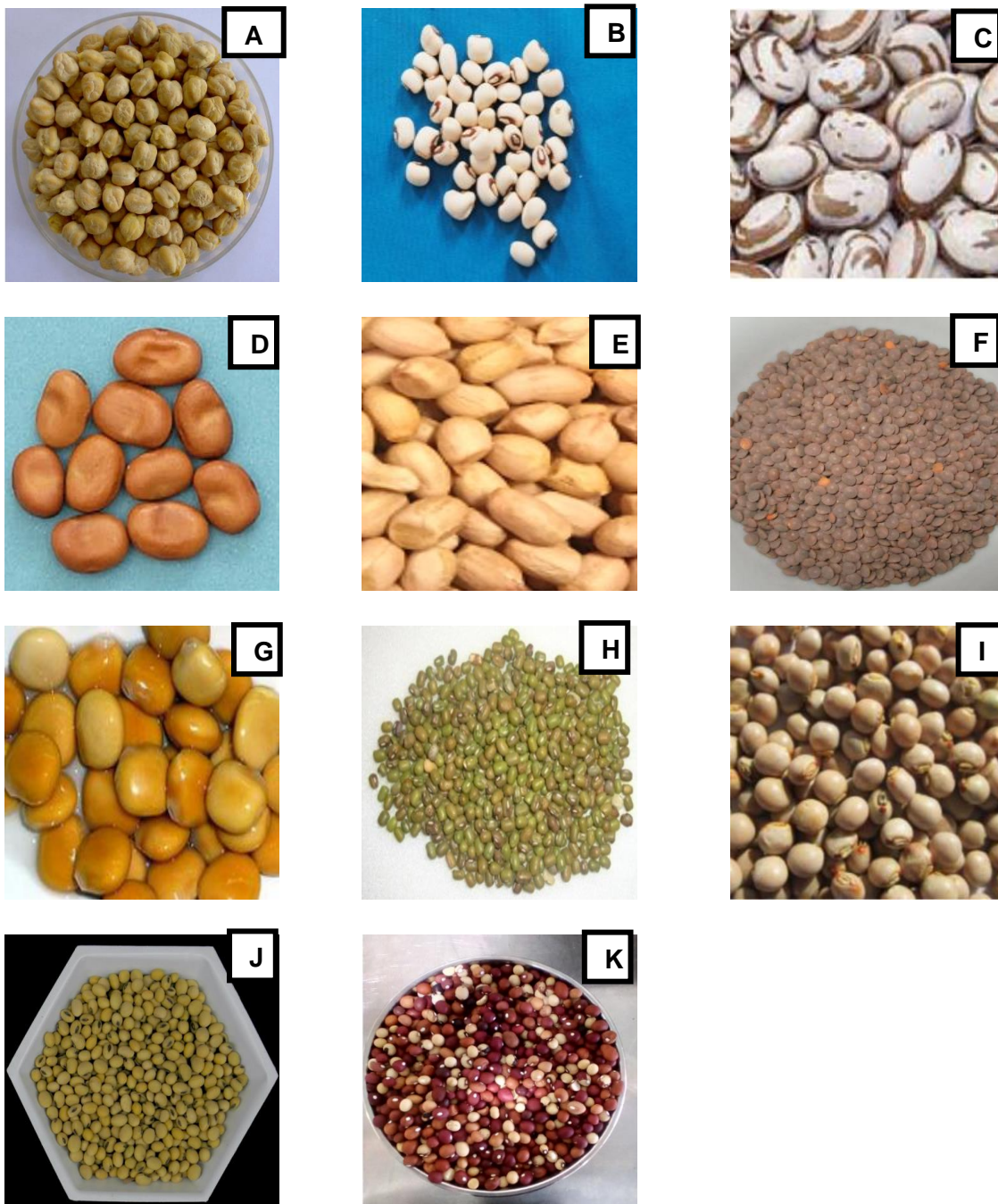


Figure 2.1 Different Legumes: A) Chickpea, B) Cowpea, C) Dry Bean, D) Faba Bean, E) Groundnut, F) Lentil, G) Lupin, H) Mung bean, I) Pigeon pea, J) Soybean, K) Bambara groundnut (^AMaheri- Sis et al., 2008, ^BKhalid and Elhardallou, 2015, ^CRezende et al., 2018, ^DNasar-Abbas et al., 2009, ^EChibarabada et al., 2017, ^GKhalid and Elharadallou, 2013, ^HShaheen et al., 2012, ^IAyenan et al., 2017 and ^JGroves et al., 2016)

2.3 Bambara Groundnut Description

The BGN also is known as *Vigna subterranea* (L) Verdc, is an underutilized indigenous African legume (Massawe et al., 2005). BGN plants can survive and adapt to drought conditions (Bonthala et al., 2016). They are categorised as beans (Yao et al., 2015), but grow the seeds underground. A BGN plant structure, as indicated in Figure 2.2 is in the form of a peanut plant consisting of stems that branch out a week after germination. It is these compound leaves that give the plant a bushy appearance. The roots that develop from the nodes of a thick taproot contain nitrogen-fixing nodules. The height of a BGN plant can go up to 0.35 m and is considered to be autogamous since it is self-pollinating (Bamshaiye et al., 2011). Bambara groundnut pods are rounded compared to peanut shells. They contain one or two seeds which are soft but which harden when dry. These seeds appear in different patterns and colours ranging from cream, red, brown and black (Baidoo et al., 2015; Goudoum et al., 2016).

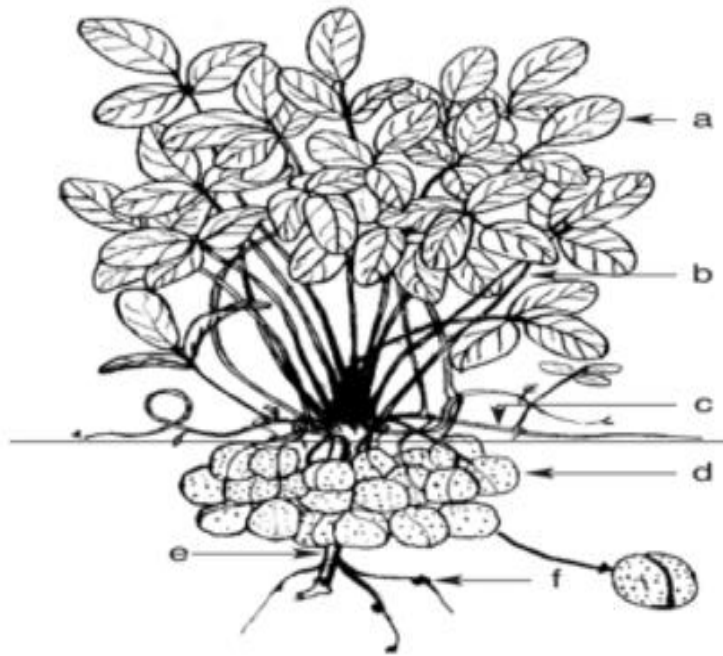


Figure 2.2 A typical BGN plant (a) leaves, (b) petiole, (c) stem, (d) pod, (e) principle root, (f) nodule (Djè et al., 2005)

2.3.1 Bambara groundnut origin and distribution

The bambara groundnut originated from West Africa (Hillocks et al., 2012; Mohammed et al., 2015) in the North-east parts of Nigeria (Mohammed et al., 2015). The groundnut got its name from a tribe called Bambara in Mali (Yao et al., 2015). Ledermann reported that the same plant grew in Garoura in Cameroon (Olukolu et al., 2012), and is distributed throughout the semi-arid region of sub-Saharan Africa (Hillocks et al., 2012), North and South America, Asia and Australia (Donkor et al., 2015). From different locations, the BGN seeds are named differently. The Tsonga people in Limpopo call them *tindluwa*.

2.3.2 Nutritional value in bambara groundnut

The nutritional composition of BGN varieties is detailed in Table 2.2. The BGN can be considered as a complete food as it contains on average, carbohydrates (57.2%), protein (18.0%), fat (6.1%), fibre (3.9%), ash (4.2%) and moisture (10.7%) (Adegunwa et al., 2014). The gross energy value of BGN exceeds that of the common grain legumes such as cowpea, lentil and pigeon pea (Bamshaiye et al., 2011). It contains many vitamins and minerals, for instance, iron, phosphorus as well as calcium (Adu-Dapaah and Sangwan, 2004) and a high level of starch (Muhammad, 2014).

Table 2.2 Composition of different bambara groundnut species

Seed colour	Proximate (%)				
	Carbohydrate	Protein	Fat	Moisture	Ash
Red	56 ± 1	20 ± 2	7 ± 2	8 ± 1	1.5 ± 1
Black	54 ± 2	21 ± 2	8 ± 1	9 ± 1	2.1 ± 1
Cream	60 ± 2	19 ± 2	1.16	10 ± 2	2.5 ± 1
Brown	56 ± 2	19 ± 2	7 ± 1	10 ± 1	2.5 ± 1

(Ojimelukwe, 1999)

2.3.3 Uses of bambara groundnut

The BGN may be utilised in many ways; for instance, it may be boiled, grilled or roasted (Ijarotimi and Esho, 2009); in the production of vegetable milk (Trivedi, 2006), yoghurt (Falade et al., 2015), snacks for example cookies (Akpapunam and Darbe, 1994), cheese (Okorie and Adedokun, 2013), salad dressings, desserts (Kudre et al., 2013), ice-creams, cakes (Eltayeb et al., 2011) sources and bread (Bamshaiye et al., 2011). Most of these products are not commercialised making BGN an underutilised legume.

2.4 Emulsions

An emulsion is a mixture of two immiscible liquids. It comprises of one liquid in the form of small droplets which is dispersed in the other liquid. The dispersed phase of an emulsion is the internal phase while the external phase is regarded as the liquid serving as the medium for the dispersed liquid (McClements, 1999). Emulsions are categorised as single emulsions and multiple emulsions. Single emulsions include O/W and W/O emulsions. Multiple emulsions include water-in-oil-in-water (W/O/W) and oil-in-water-oil (O/W/O) emulsions. O/W emulsions consist of oil droplets dispersed in water and (W/O) emulsions consist of water droplets dispersed in oil (Prichapan and Klinkesorn, 2014). Figure 2.3 details the types of emulsions. Emulsions are formed by the process of homogenisation using mechanical force, which mixes the oil and water phases by reducing (Dhankhar, 2014; Juttulapa et al., 2017) and causing the dispersion of particles. Equipment such as high-speed mixers, colloid mills and high-pressure homogenisers are used to break large droplets (Dickinson, 2009).

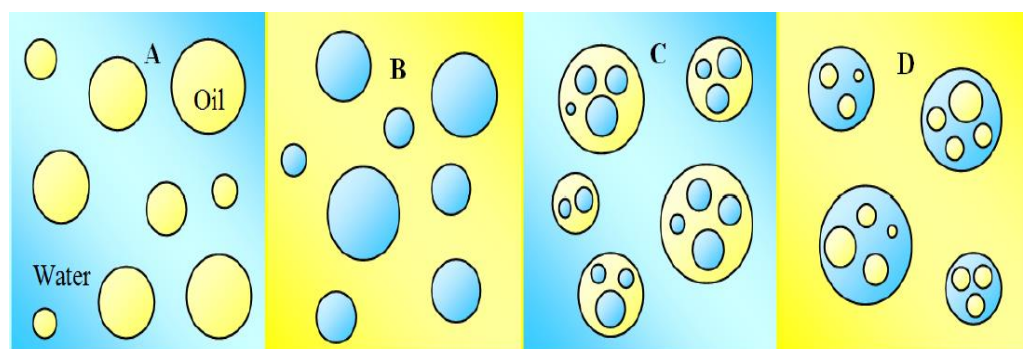


Figure 2.3 Types of emulsions: O/W emulsion, (B) W/O emulsion, (C) W/O/W emulsion (D) O/W/O emulsion (Prichapan and Klinkesorn, 2014)

2.4.1 Emulsifiers

It is difficult for polar molecules to form bonds with non-polar molecules; hence, oil and water cannot mix because water is polar and oil is non-polar. After some time, molecules tend to interact and increase the size of the droplets, which leads to the separation of oil and water (Tro, 2016). Emulsifiers are compounds that adsorb on freshly formed droplets reducing the interfacial tension between two different phases and preventing the coalescence of droplets (Dickinson, 2009). Emulsifiers enhance emulsion stability by preventing the oil and water phases from separating (Zinoviadou et al., 2011). Emulsifiers are composed of amphiphilic molecules containing both hydrophilic components usually made of polar molecules such as citric acid, lactic acid, glycerol polyglycerol and lipophilic components with molecules such as fatty acids (Bastida- Rodriguez,

2013). The reduction of the interfacial tension is due to the hydrophobic and hydrophilic components of the emulsifier bound on the oil-water interface (Lam and Nickerson, 2013). The hydrophilic-lipophilic balance (HLB) value, which ranges from 1 to 30, measures the emulsifier's affinity for the dispersed and continuous phase. A high HLB value indicates an emulsifier which contains more of the hydrophilic component which is desirable for O/W emulsions while a low HLB value indicates more of the lipophilic component and best for W/O emulsions (Liu, 2008).

Figure 2.4A represents a structure of an emulsifier which can be illustrated as a molecule consisting of a hydrophilic head and a hydrophobic tail (Puasa et al., 2011; Azarmi and Ashjaran, 2015). The aggregation of such structures forms micelles (Puasa et al., 2011) as indicated in Figure 2.4B. Emulsifiers function differently based on their chemical structure (Bastida- Rodriguez, 2013) and are categorised based on the ionic charge of their hydrophilic head (Bastida- Rodriguez, 2013) as either non-ionic or ionic [i.e anionic, cationic, amphoteric or zwitterionic] (Shchukin and Zelenev, 2016) with examples indicated in Table 2.3 to 2.5.

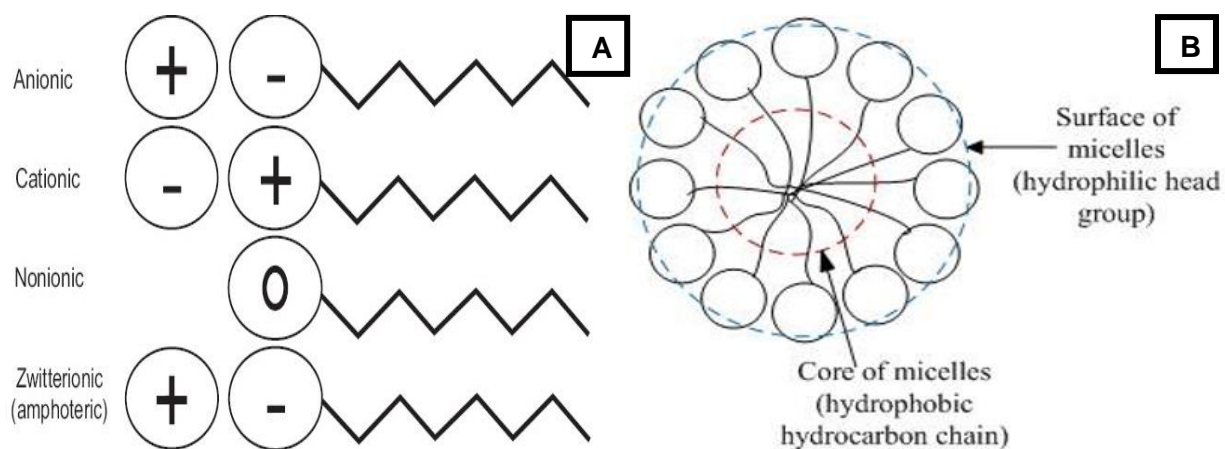


Figure 2.4 Emulsifier: A) Structure of different emulsifiers (Som et al., 2012), B) Illustration of a micelle (Puasa et al., 2011)

Table 2.3 **Examples of non-ionic emulsifiers**

Type of Emulsifier	Characteristics	Examples
Nonionic	Head group possess no ionic charge (Puasa et al., 2011).	<p>Polyglycerol Esters of Fatty acids (PGFA): Used as rheology modifiers, solubilisers or fat substitutes. The length of the PGFA chain determines its HLB value, which can then make it either an O/W emulsifier or W/O emulsifier. PGFA can be used for different oils and still maintain reduced interfacial tension (Bastida- Rodriguez, 2013).</p> <p>Polysorbates: Exhibit the most hydrophilic characteristics compared to other non-ionic emulsifiers due to their long chain (Anarjan and Tan, 2013). They stabilise dressings, confectionary, toppings and baked products. The different types include polysorbate 20, 60, 65 and 80 (Smith, 1991).</p> <p>Sucrose esters: A product of the esterification of fatty acids with sucrose. Usually used in O/W emulsions (Smith, 1991). The sucrose makes up the hydrophilic component and the fatty acids make up the lipophilic component of the sucrose esters (Anarjan and Tan, 2013).</p> <p>Monoglycerides: Used in the food industry (Chen and Rosenthal, 2015) in products such as margarine, frozen desserts and baked. Mono-and- diglycerides constitute 70% of the emulsifiers used (O' Brien, 2008).</p>

Table 2.4 **Examples of ionic emulsifiers**

Type of Emulsifier	Characteristics	Examples
Ionic Anionic	Negatively charged hydrophilic head group that attracts positively charged molecules (Puasa et al., 2011).	<p>Succinic Acid (SMG): Formed by reacting succinic anhydride and monoglyceride. It serves as a dough strengthener in yeast-raised bakery products (Friberg et al., 2004).</p> <p>Stearoyl lactylates: Sodium stearoyl lactylate (SSL) and calcium stearoyl lactylate (CSL) are produced through the esterification of steric acid with lactic acid in the presence of sodium or calcium hydroxides with fatty acids and free fatty acids as by-products. Both SSL and CSL serve as dough strengtheners (Friberg et al., 2004).</p> <p>Citric Acid (CITREM): Produced by the esterification of monoglycerides with citric acid. The hydrophilic component of CITREM dominates. Used in the food industry in products such as margarine, meat and beverage emulsions (Friberg et al., 2004).</p>
Cationic	Positively charged head group that attracts negatively charged molecules (Puasa et al., 2011) Cationic emulsifiers are not suitable for food products (Bastida- Rodriquez, 2013).	Benzalkonium Chloride: A quaternary ammonium salt (Seager and Slabaugh, 2011) possessing bactericidal properties (Denton and Rostron, 2013). Used in medicinal, cleaning and cosmetic products (Marks et al., 2016).

Table 2.5 **Examples of ionic emulsifiers continues**

Type of Emulsifier	Characteristics	Examples
Ionic	Amphoteric or Zwitterionic	<p>Head group having both positive and negative charge (Puasa et al., 2011).</p> <p>Lecithin: Composed of a mixture of phosphatides (Pan et al., 2002) such as phosphatidylcholine (PC), phosphatidylethanolamine (PE) phosphatidylinosine and phosphatidic acid (Weete et al., 1994) with PC as the major component (Pichot et al., 2013). Lecithins are mostly used in O/W emulsions (Weete et al., 1994) in which they serve as an emulsifier, viscosity regulator and a dispersing agent (Pan et al., 2002).</p> <p>Propylene Glycol Alginate: A product of the reaction between propylene oxide with alginate acid. Used to stabilise O/W emulsions mostly dressings (Hui, 2005).</p> <p>Lanolin: A natural product consisting of sterols, fatty alcohols and fatty acids. It is used in medicinal and cosmetic products (Rietschel et al., 2008).</p>

2.5 Proteins

Proteins are long chain polymers which are distinguished by their characteristics of forming dispersions or gels when added to water. Proteins possess functional properties such as thickening, gelling, emulsification and stabilization (Saha and Bhattacharya, 2010) in food products. The twenty amino acids that make up a protein molecule include alanine, arginine, asparagine, aspartic acid, cysteine, glutamic acid, glutamine, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine, valine (Kangueane, 2009). Figure 2.5 shows the chemical structure of amino acid. Denaturation is the unfolding of the protein (Fitzsimons et al., 2007) that may occur due to temperature, pressure and pH changes (Rocha et al., 2004). The isoelectric point of protein indicates a zero charge (Kirkwood et al., 2015) and protein flocculation occurs at a pH close to this isoelectric point (Burgos-díaz et al., 2016). Protein isolates are more purified than protein concentrates (Tiwari and Singh, 2012). Protein isolates may be obtained through alkaline extraction followed by acid precipitation (Sessa and Willett, 1998) while protein concentrates may be obtained by alcohol extraction followed by centrifugation and desolventisation (Yada, 2004).

2.5.1 Protein gelation

A gel is a solid interconnected network distributed in a liquid phase (Vioux et al., 2010). This network causes no steady-state flow in the system as it immobilizes the liquid phase (Tabilo-Munizaga and Barbosa-Canovas, 2005). Gels, therefore, exhibit both solid and liquid properties (Gong et al., 1999). In order to associate the protein molecules and enhance gelation, the pH should be adjusted to the isoelectric point (Fitzsimons et al., 2007). The increase in protein solubility increases protein gelation, which is affected by the amino acid composition of the protein (Witono et al., 2016).

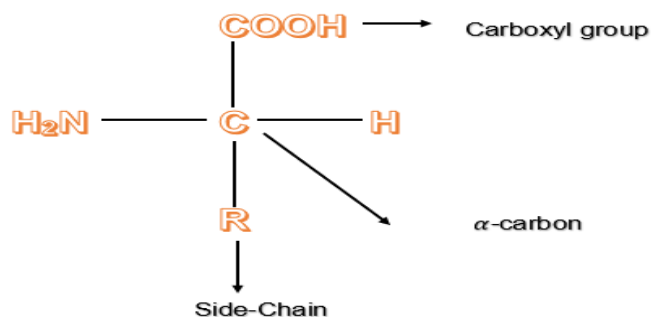


Figure 2.5 Amino acid structure (Bischoff and Schluter, 2012)

2.5.2 Vegetable proteins as emulsifiers

Vegetable proteins are suitable emulsifiers because they serve as a replacement of protein from animal sources which has high cholesterol (Nikzade et al., 2012). Though vegetable proteins contain excellent emulsifying properties, they can be affected by factors such as pH and temperature, which can lead to flocculation, with a negative impact on emulsion stability. Consequently, ionic surfactants or charged biopolymers are added to the emulsion to oppose this behaviour. Vegetable protein from soybean, pea, lupin (Burgos-diaz et al., 2016), sunflower, tomato, seed, wheat and faba bean (Nikzade et al., 2012) are reported as suitable emulsifiers.

BGN protein has several properties which are advantages for food quality. BGN protein has high water and oil absorption capacities, which promotes flavour retention. It is an excellent foaming agent that can contribute to smoothness and flavourant in foods such as deserts, bread and whipping cream, etc. It also has a high emulsifying activity which can be used as a stabiliser in food emulsions such as salad dressing, mayonnaise and ice-cream (Adebowale et al., 2011).

2.6 Emulsion Stability

Emulsion stability is the ability of an emulsion to keep its physical and chemical properties the same over a specific period. A change in the distribution of molecules in an emulsion indicates physical instability and the change in the type of molecules within an emulsion indicates chemical instability. Hydrolysis and oxidation are reactions in an emulsion that may cause chemical instability. Physical instability is the separation of the oil and water phases through creaming, flocculation, phase inversion, Ostwald ripening, coalescence as well as partial coalescence. Analytical procedures can describe any change in an emulsion that can occur over time. In emulsion instability, only one mechanism is dominant over the others (McClements, 1999). This study focuses on the physical instability properties of an emulsion.

Emulsion stability is essential in the food industry for texture and mouthfeel (Warner and Eskin, 1995) and product development (Das and Kinsella, 1990). Different food products can only be stable for a specified period. For example, cake batters can be stable for a few hours (short-term stability) and mayonnaise can be stable for several years (long-term stability). Short-term stability requires small surface-active molecules while long-term stability requires macromolecules, for example, polymers such as proteins and polysaccharides (Das and Kinsella, 1990).

2.6.1 Emulsion instability mechanisms

Manufacturing, transportation and the use of emulsions may cause emulsion destabilisation (Olatunji, 2016). Physical instability mechanisms include creaming, sedimentation, coalescence, partial coalescence, flocculation, Ostwald ripening and phase inversion. These mechanisms are illustrated in Figure 2.6

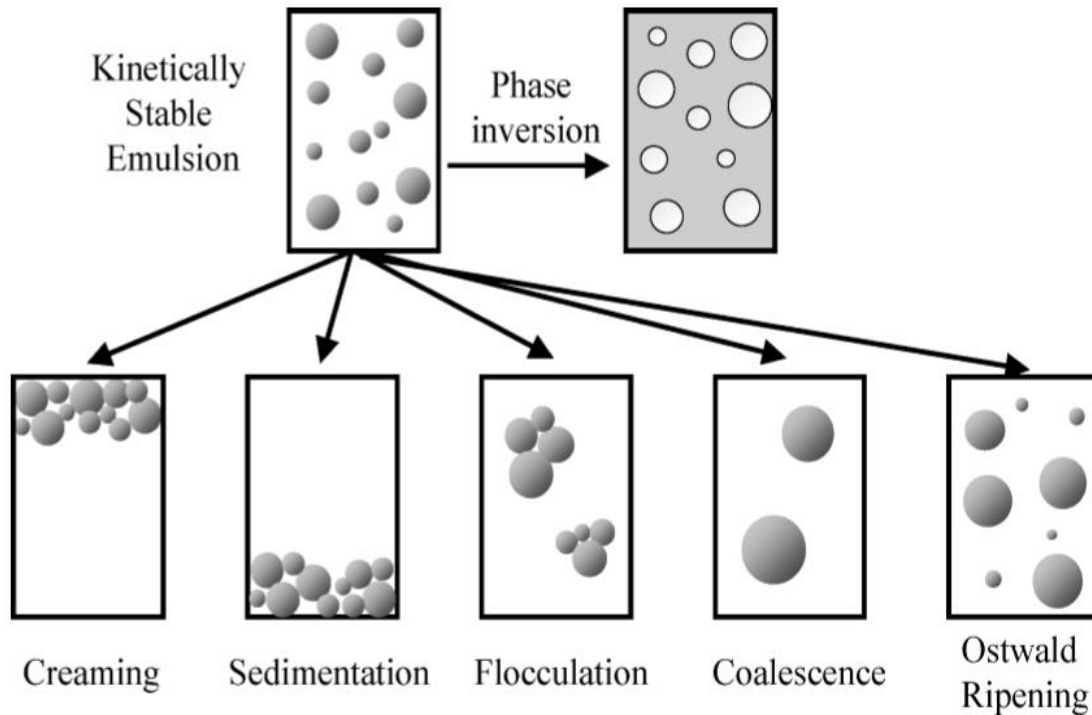


Figure 2.6 Instability mechanisms of an emulsion (McClements, 2007)

In an emulsion, the density of the internal phase (dispersed phase) and the external phase (continuous phase) is not the same. If the internal phase has a lower density, then the droplets of the internal phase will move upwards. This upward movement is called creaming. If the internal phase is denser than the external phase, then the droplets of the internal phase will tend to move downwards and this movement is called sedimentation (McClements, 2007).

Gravitational separation can be explained using Stokes law, which states:

$$v_{stokes} = - \frac{2gr^2(\rho_2 - \rho_1)}{9\eta_1} \quad \text{Equation 2.1}$$

Where v is creaming velocity, g gravitational acceleration, ρ density, η shear viscosity, r radius of the droplet. Subscript 1 refers to the continuous phase and subscript 2 refers to the dispersed phase. The upward movement or downward movement of a droplet is indicated by a positive or negative v_{stokes} , respectively (McClements, 2007).

In most cases, droplets are different in size and therefore, the Stokes equation applies to an ideal system. Creaming and sedimentation destabilisation may be decreased by the reduction in droplet size, having a low-density difference between the continuous and dispersed phase, or increasing the viscosity of the external phase (Olatunji, 2016). Velez et al. (2003) investigated the effect of polysaccharides (guar gum and xanthan gum) on the creaming rate of oil-in-water emulsions. A low polysaccharide concentration of less than 0.075% caused depletion flocculation and increasing the creaming rate. In contrast, a high polysaccharide concentration of more than 0.1% decreased the creaming rate. This decrease was caused by the polysaccharides increasing the viscosity of the external phase.

Coalescence is a process involved in the combination of droplets into a single droplet (McClements, 2007). The breaking of the interfacial film causes a decrease in the systems free energy allowing droplets to combine, resulting in coalescence (Olatunji, 2016). Oil-in-water emulsion with xanthan gum, guar gum or *k*-carrageenan stored for seven days and monitored for a change in droplet size indicated that these polysaccharides induced coalescence (Ye et al., 2004).

Partial coalescence involves a combination of two or more partly crystalline droplets forming an irregular shaped aggregate. The irregular shape of the aggregate is due to the solid crystals extending into the fluid of another droplet (McClements, 2007). The barrier formed by the emulsifier can hinder crystals from penetrating another droplet (Olatunji, 2016). Partial coalescence may or may not be required based on different products. For example, partial coalescence is not favoured in sauces, creams and milk products. However, it should be present in ice cream, butter and whipped toppings (Fredrick et al., 2010). Zhao et al. (2008) conducted a study to determine the influence of sodium caseinate and whey proteins on the texture of whipped cream. Both proteins enhanced partial coalescence with an increase in concentration. Sodium caseinate showed better stability of the whipped cream.

Flocculation occurs when two or more droplets aggregate due to attractive forces between the droplets (McClements, 2007). Droplets moving towards each other possess a greater attractive force that can displace a biopolymer weakly adsorbed or not adsorbed into the rest of the external phase leaving only less of the biopolymer remaining between the droplets. Osmotic pressure that arises enables the droplets to flocculate. Flocculation may occur through two mechanisms, namely, bridging flocculation and depletion flocculation. Bridging flocculation results due to a low concentration of an adsorbed biopolymer between droplets. Depletion flocculation results due to a biopolymer not adsorbed, creating an osmotic pressure with the surrounding external phase (Thompson et al., 2009). A study was conducted to determine the effect of xanthan gum on the

physicochemical properties of O/W emulsions stabilised by 2 wt% of whey protein with 20% menhaden oil. The amount of xanthan gum affected the stability of the emulsions. Flocculation took place between 0.02-0.15 wt% of xanthan gum. More flocculation occurred with 2 wt% xanthan gum. Without xanthan gum, emulsions did not flocculate and at 0.5 wt%, the emulsions had little or no flocculation (Sun et al., 2007).

In an emulsion, the process of smaller molecules of the dispersed phase diffusing through the continuous phase and being attached to the larger particles and causing the larger particles to grow is called Ostwald ripening (Gruner et al., 2015). Emulsions with water-soluble oil may prevent Ostwald ripening by the addition of water-insoluble oils. Ester gum has been shown to prevent destabilisation in O/W emulsions stabilised by modified starch. Ester gum comprises of non-polar polymers and is less water-soluble. Ester gum prevented Ostwald ripening by not allowing droplets to increase (Lim et al., 2011).

Phase inversion is a process that converts an O/W emulsion into a W/O emulsion and vice versa (McClements, 2007). This conversion may occur as a result of the change in temperature, change in the volume fraction of phases and by the cause of flow (Preziosi et al., 2013). During the agitation of an O/W emulsion, phase inversion can occur by increasing the oil droplet volume fraction. Phase inversion may also occur by continuously stirring for a more extended period without adding oil, enabling the water droplets to be incorporated into oil droplets (Groeneweg et al., 1998).

2.6.2 Emulsion stabilisation mechanisms

Emulsion stabilisation may occur through electrostatic or steric mechanisms. Electrostatic stabilisation occurs through the addition of charged ions onto the surface of droplets. Charged droplets, therefore, induce a repulsive force (Othman, S et al., 2012), hence no interaction would occur. This mechanism depends on the ionic strength of the medium and the droplet surface charge density (McClements and Gumus, 2016). Steric stabilisation occurs by the adsorption of an emulsifier onto the droplets creating a physical hindrance between droplets and causing them not to interact and flocculate. It depends on the thickness of the adsorbed emulsifier (Othman, S et al., 2012). The higher the thickness, the higher the repulsive force (McClements and Gumus, 2016). Figure 2.7 shows emulsion stability through steric and electrostatic stabilisation.

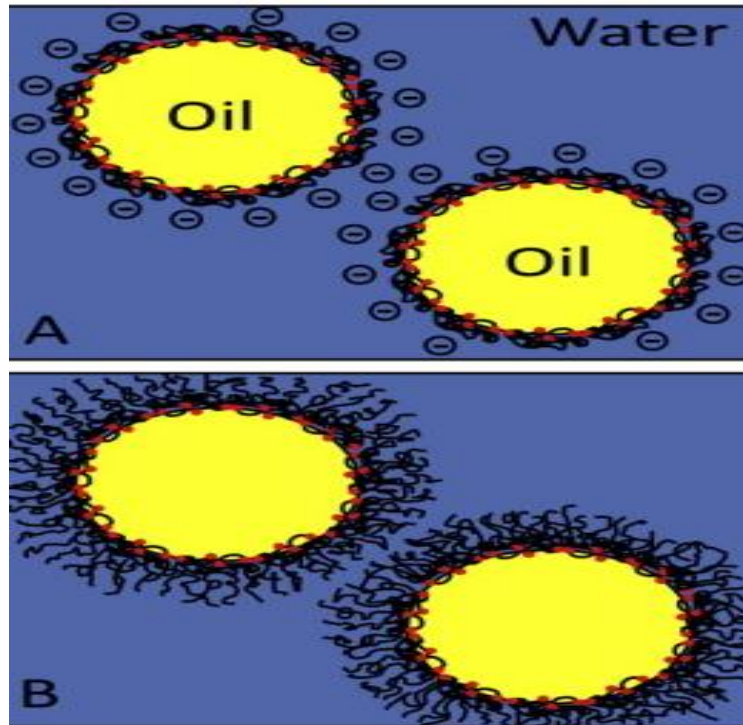


Figure 2.7 Stabilisation mechanisms of an emulsion: A) Stabilisation through electrostatic repulsion, B) Steric Stabilisation (Lam and Nickerson, 2013)

2.6.3 Emulsifying properties

Emulsifying properties describes the measure of the emulsifiers efficiency (McClements, 2005) which can be described by the emulsion stability index (ESI), emulsion activity index (EAI) and the emulsifying capacity.

The ESI measures the ability of an emulsifier to hinder droplets from undergoing aggregation (Rayner and Dejmek, 2015). The ESI is obtained by estimating the amount of separation between the two immiscible liquids when the emulsion is placed in a measuring cylinder and allowed to stand for a specific period. The ESI is estimated using equation 2.2,

$$ESI = \left(1 - \frac{V_w}{V_e}\right) \times 100 \quad \text{Equation 2.2}$$

where V_e is the volume of the emulsion and V_w is the volume of the separated bottom layer after storage time (Choi et al., 2014).

The EAI is a measure of the interfacial surface area of the droplets formed by the unit mass of the emulsifier and is obtained using equation 2.3

$$EAI = \frac{3V}{Rm} \quad \text{Equation 2.3}$$

where V is the volume of the dispersed phase, R radius of oil droplets and m mass of emulsifier (Hirst, 2013).

Emulsifying capacity measures the minimum amount of emulsifier required to stabilize an emulsion, which can also be represented by the capability of the emulsifier forming smaller droplets (Rayner and Dejmek, 2015). The emulsifying capacity is the volume of oil that is emulsified per gram of the emulsifier before the emulsion becomes unstable (Fennema, 1996).

2.6.4 Factors affecting emulsion stability

The stability of an emulsion can be affected by factors such as the emulsifier, droplets size, pH, viscosity, temperature and interfacial characteristics.

Emulsifier: The ability of an emulsifier to form a stable interfacial film and completely cover the droplet surface (Vaclavik and Christian, 2014) determines the emulsion stability. Achouri et al. (2012) studied the properties of emulsions when stabilised with soybean protein, starch and gum Arabic. The emulsions prepared with these emulsifiers were stable for 15 days. However, Achouri et al. (2012) concluded that the starch created smaller droplets than soybean protein and gum arabic during homogenisation.

Droplet size: Large droplets encourage coalescence. The difference in the densities of water and oil can cause instability in emulsions. Oil tends to move upwards because it is less dense than water. Larger droplets move upwards faster, which may break an emulsion (Vaclavik and Christian, 2014). Emulsion stability can increase by reducing particle sizes. Homogenisation conditions, the type of emulsifier and the concentration of the emulsifier affect the size of particles. In order to generate smaller particles, the concentration of the emulsifier and the homogenization time should increase (Degner et al., 2014). According to Huan et al. (2016), as the oil droplet size decreased, creaming stability increased. Chung et al. (2001) also indicated that emulsions were stable when the oil droplet sizes were smaller.

Change in pH: The pH influences the amount of electrical charge of the droplets, which affects the electrostatic interactions amongst themselves. These electrostatic interactions are dependent on the ions in the aqueous phase (Degner et al., 2014). Altering the pH may decrease the interfacial stability (Vaclavik and Christian 2014). Juttulapa et al. (2013) conducted a study on O/W emulsions stabilised with pectin-zein complexes and indicated that emulsions were more stable at pH 4 than at pH 7.

Viscosity: When an emulsion is thick, it hinders the smooth movement of droplets, causing droplets not to interact, which then enables the emulsion to stay stable for an extended period (Vaclavik

and Christian, 2014). A study conducted by Huan et al. (2016) demonstrated that stability increased with viscosity increase.

Temperature: Heating an emulsion enables droplets to gain the energy to move about, which may cause droplets to collide and interact and coalescence may result. Cooling causes oil droplets to solidify and makes the emulsion to be stable. However, freezing can cause emulsion instability because at freezing temperature, the ice crystals that form causes the film between the oil and water phase to be disrupted (Vaclavik and Christian, 2014). Liu et al. (2018) demonstrated that O/W emulsions stabilised with Perilla seed protein were stable at 70°C, unlike the emulsions at 90°C for two weeks. Bendjaballah et al. (2010) also indicated that increasing the temperature decreases the stability of O/W emulsions.

Interfacial characteristics: The thickness of the interfacial film determines the number of interactions between droplets due to colloidal forces. It is the surface charge of the interfacial layer that determines the types of ions adsorbed onto the emulsion droplets (McClements, 2016). Products formed through lipid oxidation may break the droplet and emulsifier bond by interacting better than the emulsifier with droplets and may enhance attractive forces between the droplets which can result in coalescence (Meybodi et al., 2014). The study of Schroder et al. (2017) demonstrated that emulsions become unstable as a weak interfacial film formed between the oil and water molecules due to small whey protein peptides.

2.6.5 Measurement of stability using a turbiscan

A turbiscan may also be used to determine the stability of an emulsion by vertically scanning the sample in a cylindrical tube, as indicated in Figure 2.8 and subsequently analysing it through optical characterisation. The reading head that moves up and down comprises a pulsed near-infrared light source, a transmission detector and a backscattering detector. The transmission detector receives light backscattered by the sample (Mengual et al., 1999). Emulsion instability phenomena is illustrated in Figure 2.9.

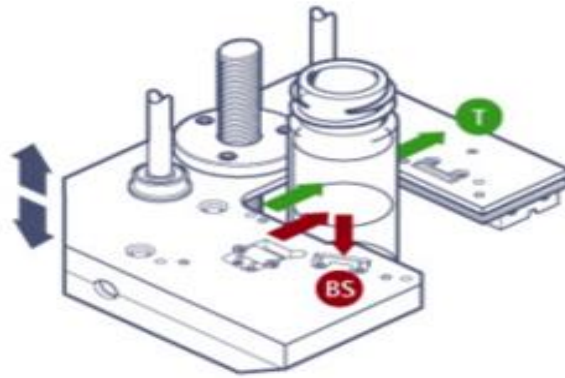


Figure 2.8 Scanning of Turbiscan Tube (Formulation, 2009)

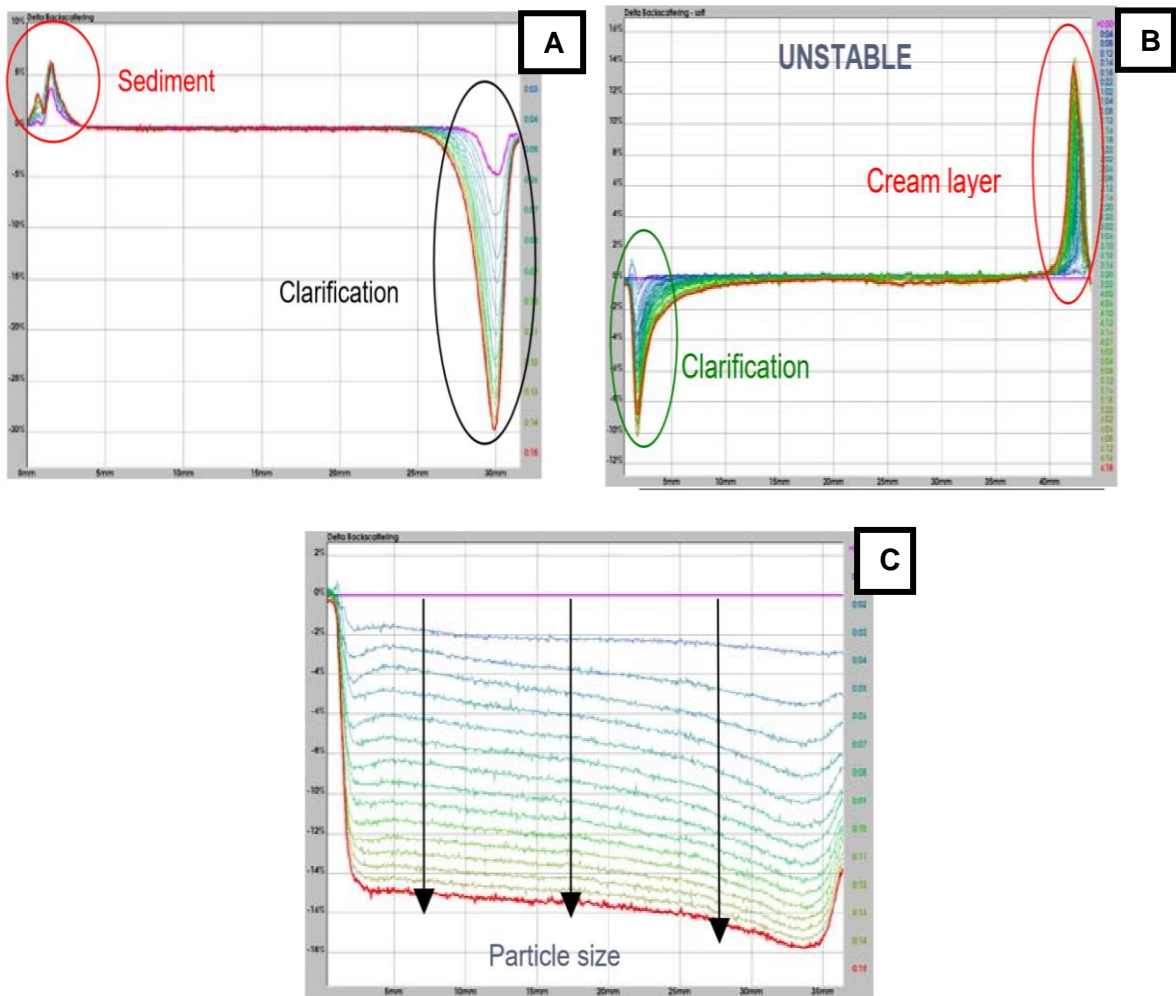


Figure 2.9 Turbiscan backscattering profiles: A) Profile of Sedimentation Phenomenon B) Profile of Creaming Phenomenon and C) Profile of Flocculation Phenomenon (Formulation, 2009)

The amount of light backscattered by the sample depends on three factors: the diameter of particles, the volume fraction and the reflective index between the internal and external phases (Formulation, 2009).

The turbiscan detects any change of particle size (indicating flocculation or coalescence) or the change in volume fraction (indicating particle migration either as creaming or sedimentation) (Formulation, 2009). Setting the time frame for a sample stability analysis depends on its expected shelf life. If the expected stability of a product is hours or a day, scanning in the turbiscan is for one hour at one-minute interval and 5 hours at 10-minute intervals. For expected stability of months, two scans to be done in a day over 15 days while storing samples in a thermo-regulated chamber after analyses is recommended (Hebishy, 2013). The turbiscan stability index (TSI) as given in equation 2.4 can be used to describe the extent of emulsion stability. (Goncharuk et al., 2017; Lu et al., 2017). The lower the TSI the greater the stability (Lu et al., 2017).

$$TSI = \sqrt{\frac{\sum_{i=1}^{n_t} (X_i - X_{BS})^2}{(n_t - 1)}} \quad \text{Equation 2.4}$$

Where X_i is the average backscattering for each interval of measurement, X_{BS} is the average of X_i and n_t number of scanning

2.6.6 Stability measuring techniques

Several changes occur within an emulsion that results in instability. For example, the change in droplet size, droplet charge, molecular interactions and flow properties of emulsions affects emulsion stability. There are specific equipment and techniques that are suitable to measure each specific change; hence, the stability of emulsions can be measured using different methods (Hu et al., 2017). Visual observation, image analysers, particle size analysers, particle charge analysers, rheology and optical (turbiscan) measurements are the conventional methods used to assess emulsion stability.

Visual Observation: Instability can be distinguished by the change in appearance, which can be seen by the naked eye. Visual observation determines the creaming and sedimentation layer. However, it is difficult to see the initial changes in an emulsion that can only be detected by analytical instruments. Though visual observation is cheap and a quick method to describe emulsion instability, other instruments need to be used to make a precise judgment of the emulsion instability (Hu et al., 2017).

Microscopy: Microscopes enable the observation of the image of droplet distribution within the emulsion. The changes in orientation may suggest instability. The use of microscopes requires dilution and the spreading of the emulsion on a slide which can alter the original nature of the

emulsion. Examples of microscopes that include the optical or electron microscopes (Hu et al., 2017).

Particle Size Analysers: Such analysers describe emulsion instability by determining the difference of the particle sizes over time. A stable emulsion entails evenly distributed small-sized oil droplets with a low variation in their sizes. The change in size into bigger sized droplets would describe instability. Examples of particle size analysers include light scattering and ultrasonic spectrometry (Hu et al., 2017).

Particle Charge Analysers: Particles surrounding droplets may affect the charge of the surface of the droplets. It is a surface charge that determines whether the droplets will repel each other and enhance stability or attract each other and cause the emulsion to be unstable. Ways of determining droplet surface charge are through microelectrophoretic techniques and electroacoustic spectroscopy (Hu et al., 2017)

Rheology: External conditions may constitute the change in viscosity of emulsions. The increase in emulsion viscosity may enhance stability. Therefore, the change in viscosity may change the flow properties, which can be described by rheological techniques. Rheometers or viscometers are the instruments which can measure the rheological properties of emulsions (Hu et al., 2017).

Turbiscan Measurements: Due to other analytical methods requiring dilution of concentrated dispersions, a turbiscan can be used to describe emulsion instability for such samples with no dilution involved. The turbiscan detects particle migration and particle growth (Mengual et al., 1999).

2.7 Rheology

Rheology is the study of the response of a material to applied force through deformation or flow (Prasad et al., 2007). The change in the material's structure under applied force is called the strain. The force per area is referred to as the stress (Tabilo-Munizaga and Barbosa-Canovas, 2005). Some materials can only begin to flow when a particular stress is exceeded and this stress is referred to as the yield stress (Norton et al., 2011) . Rheological properties of a material are affected by the material's internal structure (Pereira et al., 2007). Gases, liquids and solids will differently respond when exposed to the external force due to their physical state (Goodwin and Hughes, 2008). Rheological information of materials is essential in the design of industrial processes. A material's rheological information can be described by mathematical equations referred to as flow models. For example, these models may explain the relationship between the amount of deformation and the applied force (Hamza, 2016).

The underlying laws governing the rheological behaviour of ideal materials is Hooke's law, which describes elasticity and Isaac Newton's law, which describes the flow of materials (Chen et al., 2010). Deformations can either be elastic or irreversible. Irreversible deformations include viscous, plastic and viscoelastic deformations (Yakubov et al., 2016). An elastic material returns to its original form on the removal of the external force. A viscous material stays deformed and does not return to its original form when the applied external force is removed (Papadogiannis et al., 2009). Plastic deformation occurs when the stress goes beyond the yield stress of the material (Tylkowski and Tsibranska, 2015). The flow of materials can be described as Newtonian or non-Newtonian (Steffe, 1996) . Figure 2.10 indicates how rheology can be classified.

Sweep test rheological measurements are categorised as rotational (non-oscillatory) or oscillatory measurements (Grady, 2011; Stettin, 2016; Barzic and Ioan, 2017). A sweep test is a test having a parameter that is varied over a particular range (Kutz, 2013b) in order to measure the response for each specific value. The rheological sweep tests are performed as either small deformation or large deformation measurements (Finch, 1999). A material's rheological behaviour at large deformation such as pumping, stirring or brushing is given by rotational tests (Anton Paar, 2007). A materials rheological behaviour at small deformation is given by oscillatory tests (Finch, 1999) which provide information about the structure at rest by indicating storage stability or elasticity over a long period (Anton Paar, 2007).

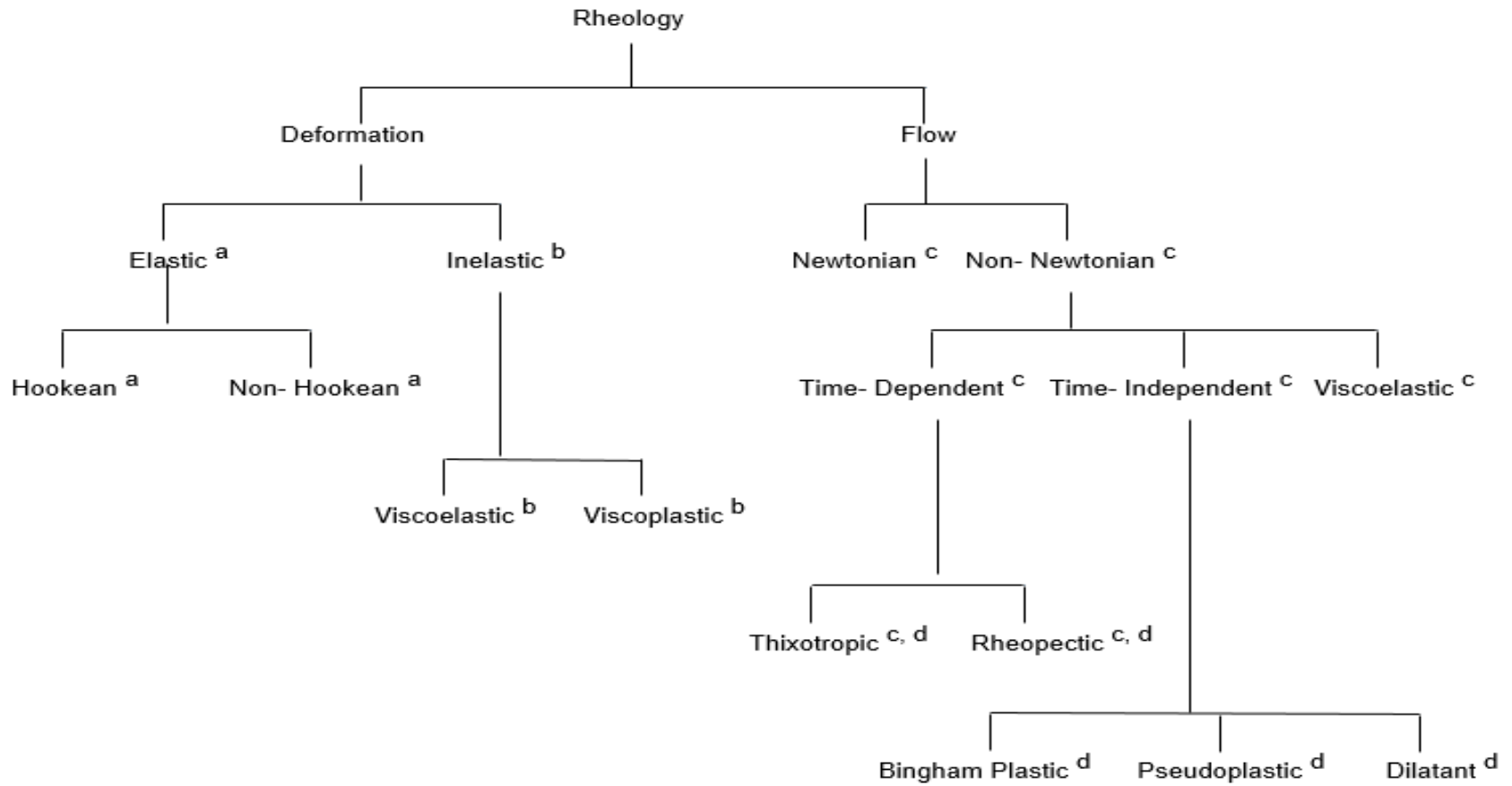


Figure 2.10 Rheological Classification (^a Pomeranz and Meloan, 1994, ^bHaupt and Sedlan, 2001, ^c Steffe, 1996, ^dGoyal, 2015)

Rotational tests measure the flow behaviour of complex non-newtonian liquids, solutions, melts and dispersions while oscillatory tests measure the viscoelastic behaviour ranging from low viscosity liquids to polymer solutions, melts, pastes, gels and solids (Mezger, 2006). Rotational sweep tests can either be ramped or performed in a stepwise manner (Mezger, 2006) and are of two types, controlled shear rate and controlled shear stress (Bourne, M, 2002; Mezger, 2006; Stettin, 2016). In a controlled shear rate test, as the shear rate is increased, the resulting shear stress is measured while the controlled shear stress test increases the shear stress and measures the resulting shear rate (Bourne, M, 2002). Both oscillatory and non-oscillatory measurements can be performed in steady state or non-steady state conditions (Grady, 2011).

At steady state conditions, rheological measurements are conducted to determine the time-independent behaviour of the material (Gallegos, 2010). Under steady shear, flocs in materials rearrange due to applied deformation creating cluster-cluster collisions. During storage there will be a point where the stress exceeds the yield stress, it is at this point where the molecular network would break and a flow would begin until steady state is reached, where an equilibrium between intermolecular forces of bond formation and bond breaking occurs (Figura and Teixeira, 2007; Kontopoulou, 2012). Steady-state shear stress sweep and steady-state shear rate sweep are measurements suitable for medium viscosity and very low viscosity materials, respectively. Dynamic stress/strain sweep is suitable for a wide range of viscosities (TA Instruments). Samples tested at equilibrium produce reliable rheological data (Ma and Hadzija, 2013). It is difficult for real systems such as food materials to reach equilibrium due to physical instability and biological activity (Peleg and Pollak, 1982). Complex materials include food (Barbosa-canovas et al., 1996) colloidal suspensions and polymer solutions. Such materials are not homogeneous, possess a disordered structure (Haavisto et al., 2014) and therefore have properties that are not consistent from one point to the next throughout their mass hence the study of rheology is difficult (Barbosa-canovas et al., 1996; Haavisto et al., 2014). Due to the complexity of structure and compositions of materials, they are difficult to model (Barbosa-canovas et al., 1996) and categorise (Haavisto et al., 2014). Therefore, steady-state rheological measurements are conducted to predict the behaviour of real materials during manufacturing and application (Pantelic, 2014). Figure 2.11 describes the rheological tests that can be performed on materials.

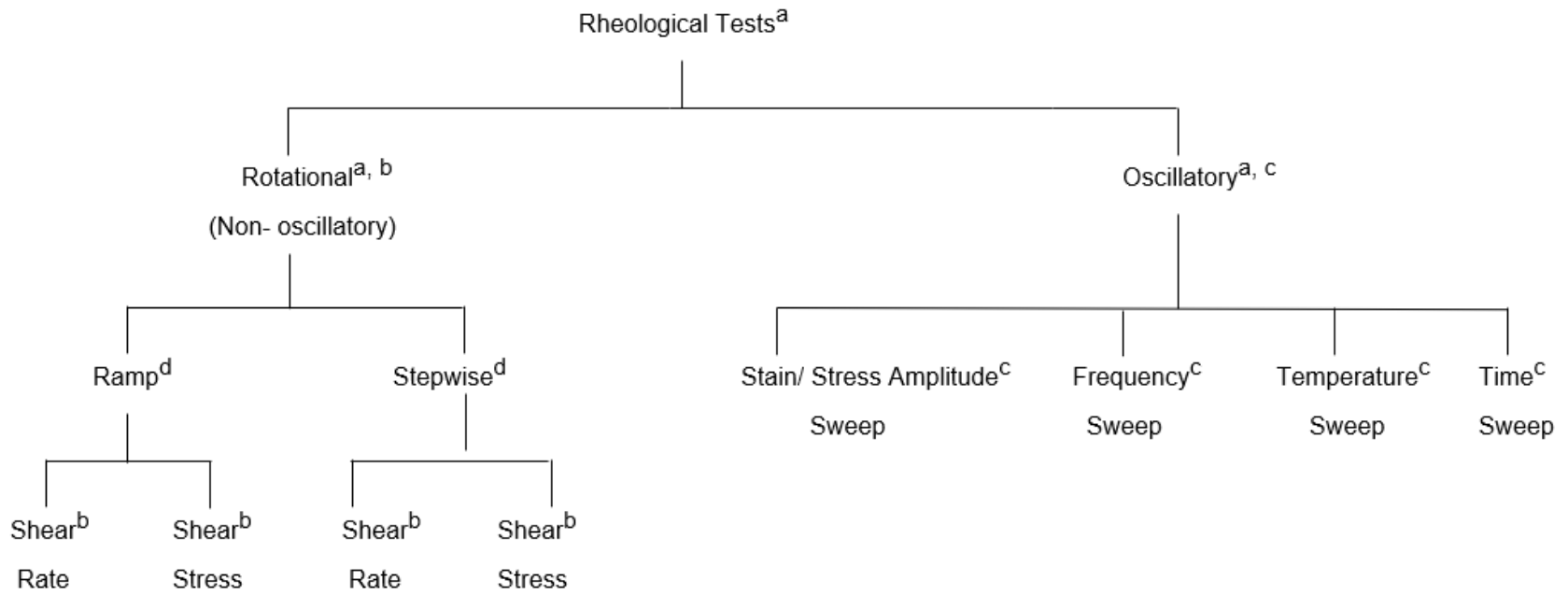


Figure 2.11 Rheological Tests (^aBarzic and Ioan, 2017; ^aGrady, 2011; ^aStettin, 2016 ; ^bBourne, 2002; ^cNorton et al., 2011; ^dMezger, 2006)

2.7.1 Flow behaviour

Flow is the continuous deformation of a material under shear stress (Howard, 1999). A material's flow behaviour is characterized by a rheogram or flow curve, indicating the relationship between stress and strain (Nielsen, 2014). Flow behaviour is categorised as either Newtonian or non-Newtonian (Nelson, 2010).

Newtonian fluids are described by the proportionality between the stress and the strain rate where the viscosity remains constant (Mohammadreza et al., 2015). Examples of Newtonian fluids include water and blood (Baqer, 2015). Newtonian fluids can be described by equation 2.5.

$$\tau = \eta \dot{\gamma} \quad (\text{Sochi, 2010}) \quad \text{Equation 2.5}$$

Where τ is the stress (Pa), η viscosity (Pa.s) and $\dot{\gamma}$ shear rate (s^{-1})

Non-Newtonian fluids show a non-linear relationship between the stress and strain rate and are categorized as time-independent, time-dependent and viscoelastic (Sochi, 2010).

Time-independent fluids characterised by the material strain rate at a particular point is dependent on the stress at the same point. The shear thinning flow behaviour is described by the decrease in viscosity with an increase in shear rate. This flow behaviour is also known as pseudoplasticity (Sochi, 2010). The shearing applied destroys the structure of the material (Jiang et al., 2014), frequent in fluids like paints, ketchup and syrups (Baqer, 2015). The property of shear thinning may indicate the pumpability (Williams, and Phillips, 2002), pourability (Batt and Tortorello, 2014) and spreadability (Tadros, 2010) of materials. Shear thickening involves the increase in viscosity of a material as the shear rate increases (Sochi, 2010), induced by molecules clustering (Yang et al., 2009). This behaviour is also known as dilatant flow (Sochi, 2010) and can occur in corn starch suspensions (Baqer, 2015). The conventional rheological models used to determine the time-independent behaviour of food systems include Power Law, Hershel Bulkley, Casson (Ofoli et al., 1987; Barbosa- Canovas, 2009) and Bingham plastic (Ofoli et al., 1987) as described by equations 2.6 (Alger, 1997; Lemus-Mondaca et al., 2016), 2.7 (Figura and Teixeira 2007; Lemus-Mondaca et al., 2016), 2.8 (Figura and Teixeira, 2007) and 2.9 (Figura and Teixeira 2007; Lemus-Mondaca et al., 2016) respectively.

$$\tau = K\dot{\gamma}^n \quad \text{Equation 2.6}$$

$$\tau = \tau_0 + K\dot{\gamma}^n \quad \text{Equation 2.7}$$

$$\tau^{0.5} = (\tau_0^C)^{0.5} + (\eta^C)^{0.5}\dot{\gamma}^{0.5} \quad \text{Equation 2.8}$$

$$\tau = \tau_0^B + \eta^B \dot{\gamma} \quad \text{Equation 2.9}$$

Where τ is stress (Pa), K consistency coefficient ($\text{Pa}\cdot\text{s}^n$), $\dot{\gamma}$ shear rate s^{-1} , n flow behaviour index (dimensionless) (where $n = 1$ represents Newtonian behaviour, $n > 1$ shear thickening (dilatant) and $n < 1$ shear thinning (pseudoplastic)), τ_0 yield stress (Pa), $\dot{\gamma}$ shear rate s^{-1} , τ_0^B Bingham yield stress (Pa), η^B Bingham viscosity ($\text{Pa}\cdot\text{s}$), τ_0^C Casson yield stress (Pa) and η^C Casson viscosity ($\text{Pa}\cdot\text{s}$). Figure 2.12 illustrates the time independent models graphically.

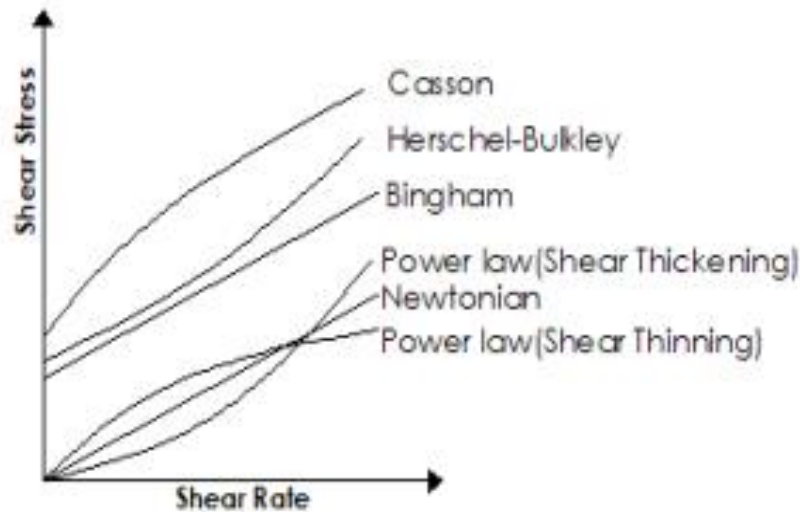


Figure 2.12 Time-independent models (Girish et al., 2018)

As rotational tests are used to describe the flow behaviour of material (Mezger, 2006), different shear rates are used. For example different processes such as mixing, spreading, chewing or pumping use a wide range of shear rates ranging from 10^{-6} to 10^3 s^{-1} (Skibsted et al., 2010). Specific processes have different shear rates, as described in Table 2.6.

Table 2.6 Typical shear rates of processes in food emulsions

Process	Shear Rate s^{-1}
Creaming	10^{-6} to 10^{-3}
Pouring	10^{-2} to 10^2
Chewing & Swallowing	10^1 to 10^2
Mixing & Stirring	10^1 to 10^3
Pumping	10^0 to 10^3

(Source: Friberg et al., 2004)

Performing a rotational steady-state test requires that the sample be equilibrated before the shear rate range can be applied. Therefore, the applied constant shear rate will enable the sample to eventually reach equilibrium conditions (Troy and Beringer, 2006).

Time-dependent fluids show a relationship between the strain rate and both the amount and the period of the applied stress, described by thixotropic and rheopectic behaviour (Sochi,

2010). Thixotropy is a behaviour of viscosity decreasing with time due to the structural breakdown of the material (Kazemian et al., 2010; Mortazavi-Manesh and Shaw, 2014). Materials such as yoghurt, gels and colloid suspensions exhibit thixotropy characteristics (Baqer, 2015). Rheopexy refers to the increase in viscosity of a material with time due to the structural build-up under shear stress (Kazemian et al., 2010). Rheopexy behaviour is typical in paint and paste (Baqer, 2015). Thixotropy and rheopexy behaviour is demonstrated graphically in Figure 2.13. Equation 2.10, 2.11 and 2.12 describes the common time-dependent models such as the Figoni and Shoemaker, Weltman and Hahn respectively.

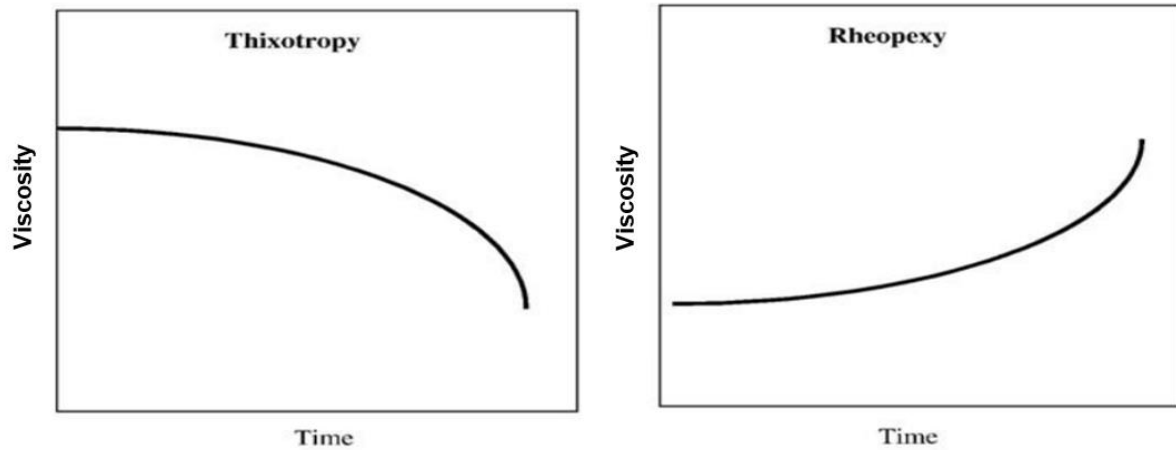


Figure 2.13 Time-dependent models (Lee et al., 2009)

Figoni and Shoemaker model is given by:

$$\tau = \tau_e + (\tau_{max} - \tau_e)\exp(-kt) \quad \text{Equation 2.10}$$

Where τ_{max} represents the initial shear stress, τ_e the equilibrium shear stress, τ is the shear stress (Pa) t the time of shearing (s) and K the kinetic constant (Basu and Shivhare, 2013)

The Weltman model is given by:

$$\tau = A - B \ln t \quad \text{Equation 2.11}$$

Where τ is the shear stress (Pa), t the time of shearing (s), A the initial stress (Pa) and B the time coefficient (Basu and Shivhare, 2013).

The Hahn model is given by:

$$\text{Log}(\tau - \tau_e) = P - \alpha t \quad \text{Equation 2.12}$$

Where τ_e indicates the equilibrium shear stress, P the initial shear stress (Pa), t the time of shearing (s) and α the sample's structural breakdown (s^{-1}) (Basu and Shivhare, 2013; Singla et al., 2013)

2.7.2 Viscoelastic behaviour

Materials that do not return to their original position when the applied force is removed can possess both viscous and elastic properties (Sochi, 2010). This behaviour is referred to as viscoelasticity (Patil et al., 2014). Examples of such fluids include lubricants and whipped cream (Baqer, 2015). In a viscoelastic material, the elastic portion of the material is represented by G' , the storage modulus, which is a measure of the stored energy within the material. The viscous portion of the material is represented by G'' , the loss modulus which is a measure of the energy in the form of heat that is released within the material (Amirdivani et al., 2013). The yield stress is the minimum stress that enables the material to start flowing due to the broken material structure (Augusto et al., 2012) indicating the non-linear region (Carmona et al., 2014).

An oscillatory test involves setting a sample under sinusoidal deformation and determining the resulting stress response over time. The stress response of materials differs and can be represented as elastic, viscous and viscoelastic, as shown in Figure 2.14. For elastic materials, there is a direct proportionality between the deformation and stress is indicated by having the deformation being in phase with the stress. Viscous materials are indicated by having the stress response out of phase by 90° . For viscoelastic materials, the stress response has a phase angle that lies between 0° and 90° (Wyss et al., 2007). The amplitude, frequency, temperature and time sweep tests are some of the oscillatory experiments that can be conducted to determine the viscoelastic behaviour of a material.

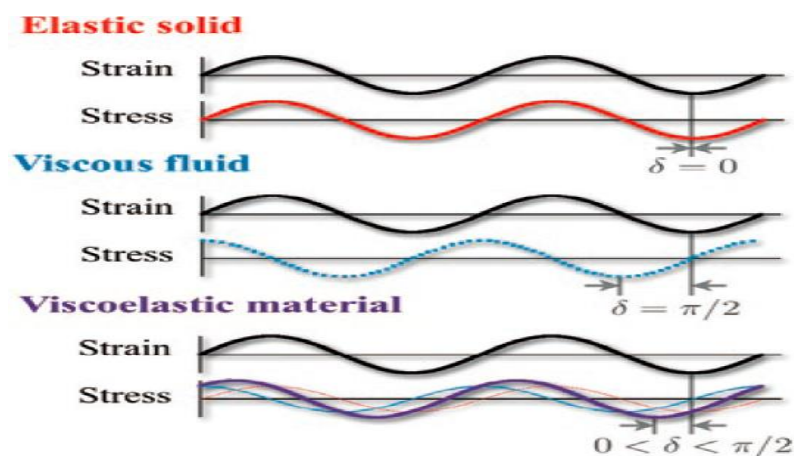


Figure 2.14 Stress response indicated in an elastic, viscous and viscoelastic material (Wyss et al., 2007)

The primary purpose of the amplitude sweep is to determine the limit of the linear viscoelastic region LVR (Mezger, 2006), and is defined as the value at which the storage modulus begins to deviate from its linear path. It is the storage modulus that tends to decrease first; hence, it is used to describe the limit value (Agarwal et al., 2016). The G' and G'' curves running below the limit value remains constant thus representing the stability (Mezger, 2006) and the gel

strength of the samples (Doan et al., 2015). Also, the amplitude test can be used to determine the flow point (Mezger, 2006). The loss tangent value can also be determined to represent the ratio of the viscous to elastic portion of the sample (Gunasekaran and Ak, 2000). Amplitude tests are conducted at varying strains while keeping the frequency constant. A low frequency of 1 HZ is commonly used (Mezger, 2006; Farid, 2010).

Oscillatory shear tests consist of small amplitude oscillatory shear (SAOS) tests and large amplitude oscillatory tests (Melito et al., 2012). For SAOS tests, small strain or stress is applied (Haghighi and Rezaei, 2012), which does not destroy the material's structure indicates the linear viscoelastic region (Trujillo-Cayado et al., 2017). Large amplitude oscillatory shear (LAOS) tests can provide elastic and viscous characteristics for complex fluids as well as sensory and textural properties in food. As the strain amplitude increases, the material's behaviour moves from the linear to the non-linear region (Carmona et al., 2014). Figure 2.13 represents a diagram of a sweep test with increasing strain at a fixed frequency. A strain level is chosen in the linear region and used in conducting the frequency sweep (Mezger, 2006; Norton et al., 2011)

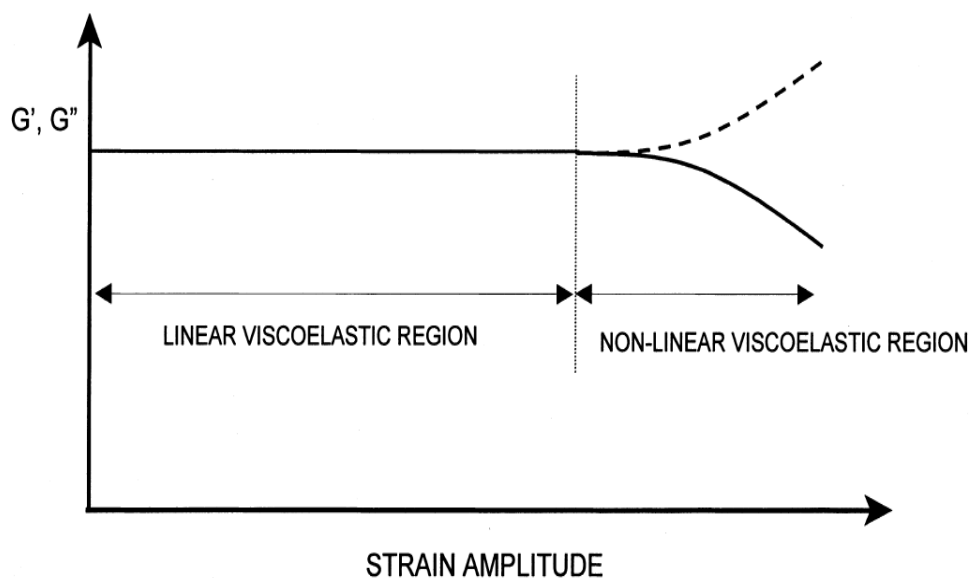


Figure 2.15 Relationship between strain and fixed frequency (Gunasekaran and Ak, 2000)

Frequency sweeps at varying frequencies and a constant amplitude are performed to obtain G' and G'' (Mezger, 2006). A frequency of 0.01 to 100 rad/s for food applications is usually used (Kutz, 2013a). Viscoelastic data from frequency sweeps can be used to categorise dispersions into one of the following common types:

1. A dilute polymer solution: where the G' is smaller than the G'' across the entire range of frequencies and where both moduli are dependent on the frequency (Tashiro et al., 2010).
2. An entanglement network: this is indicated by G' and G'' crossing at the middle of the frequency range and having a solid-like structure at higher frequencies (Farahnaky et al., 2010).
3. A strong gel: where G' is much greater than G'' , both moduli being independent of frequency (Tashiro et al., 2010). A strong gel can be represented by $\frac{G''}{G'}(\omega) \leq 0.1$ (Patel et al., 2015).
4. A weak gel: where G' is slightly greater than G'' , both moduli slightly dependent on frequency (Tashiro et al., 2010). A weak gel can be represented by $\tan \delta$ being higher than that of a strong gel (Van Vliet, 2014).

A frequency sweep test is useful in simulating short-term storage stability (high frequencies) and long-term storage stability (low frequencies) (Mezger, 2006). A frequency sweep test may also be used to describe slow movements using low frequencies and fast movements using high frequencies (Mezger, 2003).

Temperature sweep test describes the effect that temperature has on G' and G'' at constant frequency. This test can be used to describe the gel formation of protein dispersed samples (McKenna, 2003). Due to different food products requiring different storage conditions in order to maintain quality (Booker et al., 2004), some foods are stored at refrigeration temperature (5°C) and others at cold to ambient temperature (10 to 35°C) (Ray and Bhunia, 2007). This project used the temperature sweep to determine the effect of temperature ranging from 0 to 40°C. The purpose of increasing up to 40°C was to determine the behaviour of the emulsions above room temperature.

Time sweep tests are performed to determine G' and G'' as a function of time at constant frequency and temperature (McKenna, 2003; Bui et al., 2012). It can be used to determine the gelling time of the material (Bui et al., 2012).

2.7.3 Rheometer geometries

Different geometries of the rheometer such as cone-and-plate, plate-plate and concentric cylinders are used (Mykhaylyk et al., 2016). The cone-and-plate and plate-plate geometries are typically used for pastes, gels and concentrated suspensions (Kulkarni and Shaw, 2016) whereas concentric cylinder geometries are for low viscosity fluids (Wasserscheid and Welton, 2008; Kulkarni and Shaw, 2016).

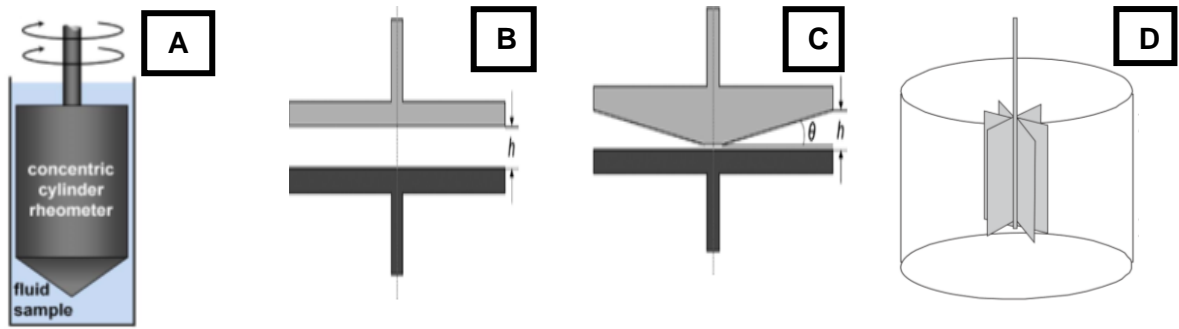


Figure 2.16 Rheometer Geometries: A) Concentric cylinder, B) Plate- to- plate, C) Cone- to- plate D) Vane (^ARoxworthy et al., 2014, ^BSong et al., 2017, ^CSong et al., 2017, and ^DSchwartzentruber et al., 2006)

2.8 Functionality of Legumes in O/W emulsions

From the study of Nikovska (2012), O/W emulsions stabilised by soy protein isolates were more oxidatively stable than those stabilised by whey protein isolates. This implies that they were able to resist oxidation (Martinez- Force et al., 2015) which would negatively affect the flavour, texture, appearance and nutritional quality (Decker et al., 2010) of the emulsions. The study further demonstrated that the apparent viscosity of the O/W emulsions increased with the increase in soy protein isolate concentration. Shear thinning was observed for these emulsions. Félix et al. (2019) demonstrated that O/W emulsions stabilised by chickpea protein had more stability than those stabilised by faba bean protein as their turbiscan backscattering profiles were more constant after 28 days. Though both the emulsions stabilised by chickpea protein and faba bean protein demonstrated gel properties, the O/W emulsions stabilised by chickpea had high viscoelastic properties at a pH of 2.5 (Félix et al., 2019). Work has been done on the functionality of BGN indicating that both BGN flour and protein had considerable water and oil absorption capacities (Eltayeb et al., 2011). BGN milk increased protein and decreased fat in yoghurt (Adebanke et al., 2017). Brough et al. (1993) studied the potential of bambara groundnut in vegetable milk production. The study indicated that a group of taste panellists preferred BGN milk more than cowpea, soybean and pigeon milk. Brough et al. (1993) also concluded that BGN milk had a lighter colour than cowpea milk. Gabriel et al. (2013) and Adeyi et al. (2014) concluded that BGN flour stabilised O/W emulsions. Adeyi et al. (2014) also reported that the O/W emulsions had yield stress and shear thinning properties. Previous work performed on BGN demonstrated insignificant information on the stability and rheological properties of O/W emulsions stabilised by BGN protein

2.9 Chapter Summary

Emulsions are a mixture of two immiscible liquids which are held together by an emulsifier. The quality of the emulsion can be characterised by the use of a turbiscan, rheometer and an image analyser. Protein isolates from various legumes are reported to be efficient in stabilising O/W emulsions. Work has been done on the use of BGN flour in emulsions however these studies did not focus on the potential of BGN protein specifically from the brown seeds in O/W emulsions.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Materials and Equipment

Bambara groundnut seeds purchased from Thusano Products in Limpopo (Makhado) province were milled using a Fritsch Pulverisette 19 Cutting mill to produce BGNF which was used for protein extraction. Sodium hydroxide (NaOH) and hydrochloric acid (HCL) were used as pH adjusting agents. A 212 μm sieve was used to sieve the flour and a weighing balance to measure its weight. An overhead stirrer was used for mixing distilled water and BGNF during protein extraction. An Ortoalresa Digtor 21 centrifuge was used for concentrating solids from liquid. Trays were used for protein drying. A porcelain mortar and pestle were used for grinding the protein. A polyethylene ziplock bag was used to store protein which was placed in a cool environment (fridge). A D-lab homogeniser was used for homogenising protein, oil and water. A Discovery Hybrid rheometer using a concentric cylinder geometry (DIN rotor and cup with specifications: bob diameter: 28 mm; bob length 42 mm; cup diameter 30.4 mm) was used to conduct rheology tests on O/W emulsions. A turbiscan was used to conduct stability tests. All above mentioned chemicals and equipment were obtained from the Cape Peninsula University of Technology (Chemical Engineering department) and Sunflower oil purchased from a local supermarket. A Zeiss Axio light microscope from Stellenbosch University was used for emulsion imaging.



Figure 3.1 Main Equipment used: A) D-Lab Homogeniser, B) Discovery Hybrid Rheometer and C) Turbiscan MA 2000

3.2 Methodology

3.2.1 Preparation of bambara groundnut flour

The BGN's were sorted into different colours and the brown seeds were milled using a Fritsch Pulverisette 19 Cutting mill producing brown BGN flour.

3.2.2 Protein extraction from bambara groundnut flour

Isoelectric precipitation method was used to extract protein from BGNF as described by (Chalid et al. (2015) with some modification. BGNF was mixed with distilled water using a ratio of 1: 10 (w/v) and the mixture was stirred for 5 minutes. The pH of the mixture was adjusted to 8 using 1M of NaOH. The mixture was stirred for 1 hour and centrifuged at 3500g for 30 minutes. Solids were separated from the first supernatant and discarded. The pH of the first supernatant was adjusted to 4 using 1 M HCl. The adjusted supernatant was stirred for 1 hour and followed by centrifugation at 3500g for 30 minutes. The second supernatant was discarded. The solids which were the resulting protein was spread out on a tray and air dried for 48 hours. The dried protein was ground using a porcelain mortar and pestle, placed in a polyethylene ziplock bag and stored in a fridge until required for use. The protein extraction process is demonstrated in Figure 3.2.

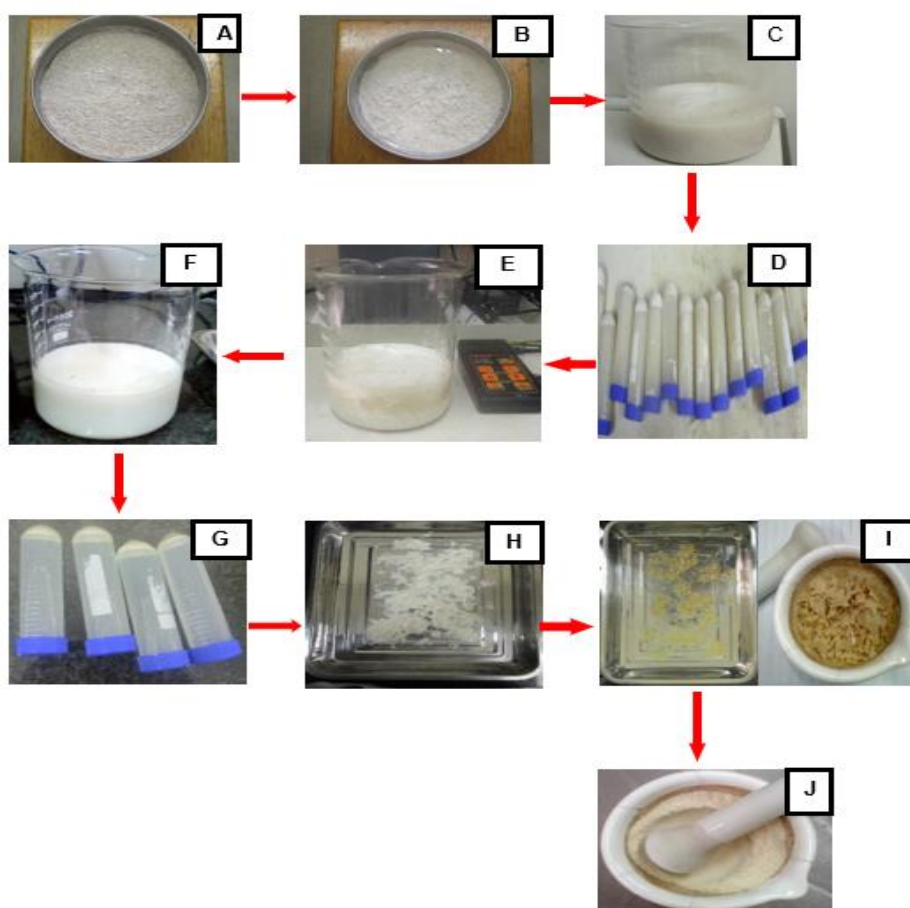


Figure 3.2 Protein Extraction process: A) Brown Flour, B) Sieved brown flour, C) Mixture of distilled water and brown flour adjusted by NaOH, D) Centrifuged mixture after adjusting by NaOH, E) Colour change of first supernatant when adjusted by HCl, F) First supernatant after adjusting by HCl and after mixing, G) Centrifuged mixture after adjusting by HCl, H) Protein Airdrying, I) Dried protein ready for grinding, J) Fine protein powder

3.2.3 Protein characterisation

Amino acid characterisation of the extracted protein was conducted using Waters Acquity Ultra Performance Liquid Chromatograph fitted with a photodiode array detector. Derivatised amino acids were used for characterisation where the following derivatisation procedure was used:

Borate buffer (70 μ l) was pipetted into a vial and mixed with 10 μ l of diluted protein sample. AQC reagent (Waters Accq.Tag Ultra Reagent) (10 μ l) was added into the mixture. The vial was capped and vortexed for well mixing. The vial was incubated for 10 minutes at 55°C. After 10 minutes the sample was placed on an autosampler tray for analysis (Waters Corporation, 2007).

3.2.4 Emulsion formation using different protein/oil/water compositions

A D-optimal mixture was used to estimate the effect of protein isolate, oil and water on the stability of oil-in-water emulsions. The emulsion compositions consisted of protein ranging from 6 to 15%, oil ranging from 32.22 to 39% and water ranging from 55 to 60%. The proportions in the emulsion at any instance added up to 100%. The experimental design comprised of 14 compositions.

O/W emulsions were formulated by dissolving protein isolate in distilled water and homogenised at 20 000 rpm for 10 minutes. The sunflower oil was then added to the protein isolate solution and the mixture homogenised at 20 000 rpm for 10 minutes according to the emulsion formulation described by Zungur et al. (2015) with some modification. Homogenisation was conducted using a D- lab homogeniser. However, when using this procedure some of the emulsions would form lumps and were more like cream than emulsions. Secondly due to the high speed and high power of the D-lab homogeniser, the samples were very hot which would therefore affect its properties. Due to these reasons, the procedure was changed to using a speed of 10 000 rpm to homogenise distilled water and protein for 1 minute and adding oil to the protein solution while homogenising at the same speed for 5 minutes. Once the O/W emulsions were formed, they were subjected to tests described in section 3.2.5 to 3.2.11. Turbiscan and rheological tests were performed immediately after formulation in duplicates for all emulsions.

3.2.5 Visual observation

All emulsions were monitored visually to determine how long the emulsions remained stable. The emulsion stability index was obtained according to the equation described in section 2.6.3:

$$ESI = \left(1 - \frac{V_w}{V_e}\right) \times 100$$

where V_e is the volume of the emulsion and V_w is the volume of the separated bottom layer after storage time (Choi et al., 2014).

The emulsions were filled to the top of the container and its volume was 12.5 ml.

Table 3.1 Experimental Design

Emulsion	Component (wt%)		
	Protein	Oil	Water
1	6.00	39.00	55.00
2	9.25	33.25	57.50
2a	9.25	33.25	57.50
3	6.00	36.26	57.74
4	15.00	30.00	55.00
5	6.00	34.00	60.00
6	12.53	30.00	57.47
7	10.50	34.50	55.00
8	8.14	36.63	55.23
9	10.00	30.00	60.00
9a	10.00	30.00	60.00
4a	15.00	30.00	55.00
10	12.78	32.22	55.00
1a	6.00	39.00	55.00

3.2.6 Emulsion imaging

A Zeiss Axio light microscope at 20X magnification was used for capturing the images of the emulsions where few drops were placed on a slide and spread out to achieve a thin layer.

3.2.7 Stability test using a turbiscan

A turbiscan MA 2000 was used to describe the stability of emulsions. A transparent 80 ml tube containing an O/W emulsion was placed in the turbiscan and scanned over 5 hours at every 10 minute interval (Hebishy, 2013). For each scan, a different coloured backscattering graph was plotted. From the backscattering intensity, the clarification and coalescence phenomena were determined as well as the migration rate.

3.2.8 Determination of migration rate

The migration rate of the small droplets was used to determine how fast or slow they moved thus demonstrating emulsion instability. After scanning samples at the set time, peaks were identified in the bottom zone of the backscattering profiles. It is the variation of the peak width at a particular height that illustrates that the migration of small particles took place. The corresponding thickness curves of the scanned samples were obtained from the migration software on the turbiscan. The linear part of the curve of the peak thickness versus time was identified and zoomed and its slope was used as the migration rate (Huck- Iriart, 2011; Herrera 2012).

3.2.9 Determination of turbiscan stability index

The turbiscan stability index (TSI) was obtained by using equation 2.4:

$$TSI = \sqrt{\frac{\sum_{i=1}^{n_t} (X_i - X_{BS})^2}{(n_t - 1)}}$$

where X_i is the average backscattering for each interval of measurement, X_{BS} is the average of X_i and n_t number of scanning

3.2.10 Modelling of migration rate and turbiscan stability index data

Design expert version 10 software was used to model the migration rate and turbiscan stability index (TSI) data. The migration rate and TSI data was modelled using the quadratic and linear mixture model respectively where the p-value was used to determine the significance of the protein/oil/water composition in affecting the migration rate and the TSI. The optimum was obtained based on the migration rate and TSI responses where the goal was to minimise both the migration rate and the TSI.

3.2.11 Rheological tests

Rotational and oscillatory tests were conducted to determine the flow and viscoelastic behaviour of O/W emulsions respectively. A concentric cylinder geometry was used to perform measurements at a gap of 1 mm. The oscillatory tests included the amplitude, frequency, temperature and time sweep tests. Before oscillatory tests were conducted, the samples were equilibrated for 10 minutes (Adeyi et al., 2014).

Rotational Steady State Test: The steady-state test was conducted by firstly subjecting samples under a constant shear rate of 100 s^{-1} for 10 minutes. After that, the shear rate was varied from 10^{-2} to 1000 s^{-1} at 25°C . The apparent viscosity was obtained from the relationship between the shear stress versus shear rate.

The data obtained from the rotational steady state test was fitted to conventional time-independent models (Power law, Bingham, Herschel-Bulkley and Casson) using Matlab 2017 where a nonlinear regression tool was used and the Levenberg- Marquardt algorithm was adopted as the optimisation tool in order to calculate the R-squared, adjusted R-squared, sum of square error (SSE) and root mean square error (RMSE) (Khalil and Mohamed Jan, 2012).

Amplitude Oscillatory Sweep Test (Strain sweep): Strain sweep test was conducted at a strain range of 0.1 to 1000% under a fixed frequency of 1 Hz. The linear viscoelastic region (LVR) and the transition point (where $G' = G''$) was extracted from the plot.

Oscillatory Frequency Sweep Test: The frequency sweep test was conducted at a frequency range of 0.01 to 100 Rad/s (Kutz, 2013a) at a fixed temperature 25°C and a constant strain of 0.2% obtained from the amplitude sweep test. The G' and G'' were obtained at the varying frequencies demonstrating the effect of frequency on the rheological properties of the O/W emulsions.

Oscillatory Temperature Sweep Test: The O/W emulsions were subjected to a temperature of 0 to 40°C at a constant strain of 0.2% and a constant frequency of 1 Hz to determine the effect of storage temperature.

Oscillatory Time Sweep Test: The effect of time on the rheological properties of the O/W emulsions were determined by subjecting the samples for 1 hour at a constant strain of 0.2%, frequency of 1 Hz and temperature of 25°C.

3.2.12 Data analysis

Analysis of Variance (ANOVA) was used to establish the difference among the migration rate and the TSI responses for each formulation as described in Table 3.1. The migration rate and TSI variables were fitted to a quadratic and linear mixture model, respectively. The lack of fit p-value was used to describe the model adequacy. Numerical optimisation was used to establish the optimum formulation with minimum migration rate and TSI (Design-Expert version 10).

CHAPTER FOUR RESULTS AND DISCUSSION

4.1 Introduction

This section provides the results and discussion of the stability and rheological tests performed on O/W emulsions stabilised with BBGN protein isolates. The original experimental design had 14 emulsion compositions however that was reduced to 10 as the typical results of the repeating emulsions are presented.

In this study, as described in Table 4.1, a low protein emulsion (LPE) comprised of 6% protein concentration, a medium protein emulsion (MPE) comprised of 8.14 to 10.50% protein concentration and a high protein emulsion (HPE) comprised of 12.53 to 15.00% protein concentration. The emulsions were arbitrarily classified as low to high protein emulsions based on visual appearance. The LPEs were liquid-like. The HPEs were thick and not flowy as the LPEs. The MPEs were more viscous than the LPEs however not as thick as the HPEs.

Table 4.1 Emulsion Categories

Emulsion				
Category	Emulsion	Protein %	Oil %	Water %
LPEs	1	6.00	39.00	55.00
	3	6.00	36.26	57.74
	5	6.00	34.00	60.00
MPEs	2	9.25	33.25	57.50
	7	10.50	34.50	55.00
	8	8.14	36.63	55.23
	9	10.00	30.00	60.00
HPEs	4	15.00	30.00	55.00
	6	12.53	30.00	57.47
	10	12.78	32.22	55.00

4.2 Amino Acid Composition of the BBGN Protein Isolate

Protein obtained from the extraction procedure had a yield of 16.6%. The total amino acid composition of the BBGN protein isolate was 85.6 g/100 g protein isolate. Glutamic acid was the highest with 13.4 g/100 g protein isolate, as shown in Table 4.2. Methionine was the least with 1.5 g/100 g protein isolate.

Table 3.2 Amino Acid Composition of Legume Protein Isolates (g amino acid/100 g protein isolate)

Amino Acid	Quantity (%)					
	BBGN ¹	BBGN ²	Lupin ³	Soy ³	Pea ³	
Essential	Methionine	1.5 ± 0.0 ^a	1.4 ± 0.75	0.2	0.3	0.3
	Isoleucine	3.2 ± 0.0 ^b	4.1 ± 0.90	1.5	1.9	2.3
	Threonine	3.6 ± 0.1 ^c	4.7 ± 0.21	1.6	2.3	2.5
	Valine	3.7 ± 0.0 ^c	5 ± 0.39	1.4	2.2	2.7
	Histidine	4.4 ± 0.1 ^d	2.6 ± 0.65	1.2	1.5	1.6
	Lysine	5.0 ± 0.1 ^e	6.1 ± 0.43	2.1	3.4	4.7
	Leucine	6.7 ± 0.0 ^g	6.5 ± 0.14	3.2	5	5.7
	Phenylalanine	8.8 ± 0.4 ⁱ	5.3 ± 0.40	1.8	3.2	3.7
Non-essential	Alanine	3.1 ± 0.0 ^b	3.7 ± 0.32	1.7	2.8	3.2
	Arginine	6.9 ± 0.0 ^g	7.8 ± 0.51	5.5	4.8	5.9
	Aspartic acid	8.1 ± 0.2 ^h	11.9 ± 0.07			
	Cysteine			0.2	0.2	0.2
	Glutamic acid	13.4 ± 0.2 ^j	15.1 ± 0.06	12.4	12.4	12.9
	Glycine	3.1 ± 0.0 ^b	2.6 ± 0.05	2.1	2.7	2.8
	Proline	3.1 ± 0.0 ^b		2	3.3	3.1
	Serine	6.0 ± 0.1 ^f	5.7 ± 0.59	2.5	3.4	3.6
Tyrosine	5.0 ± 0.2 ^e	7.4 ± 0.51	1.9	2.2	2.6	

Mean values with different alphabetic subscripts in the same column differ significantly from each other ($p \leq 0.05$). Present study¹, Adebowale et al. (2011)², Gorissen et al. (2018)³.

The amino acid profile of this study is in agreement with that of Adebowale et al. (2011) who also described the presence of same amino acids in BBGN protein isolate except for proline as described in Table 4.2. Adebowale et al. (2011) indicated that glutamic acid was also high with 15.1 g/100 g protein isolate and methionine the least with 1.4 g/100 g protein isolate. Gorissen et al. (2018) reported the same amino acids for lupin, soy and pea protein isolate except for aspartic acid. The BBGN protein isolate of this study did not contain cysteine and Adebowale et al. (2011) did not report its presence as well. Though Gorissen et al. (2018) reported the presence of cysteine for lupin, soy and pea protein isolates, it was in low

quantities. The quantity of amino acids of this study compared to that of Adebowale et al. (2011) and Gorissen et al. (2018) were different probably due to the difference in the method of extraction. Interactions of amino acids with other compounds may form sweet, bitter or sour flavour in food. However, the changes in amino acids that may occur due to processing may alter the flavour of the sample (Hui, 2005). According to Hui, (2005), amino acids can also provide taste in meat, fish and dairy products. As a protein chain contains 20 amino acids (Kanguane, 2009), BBGN protein may add flavour in associated food products as it contains 16 (catergorised as essential and non-essential in Table 4.2) of the 20 amino acids that make up the protein chain.

4.3 Stability Characteristics of O/W Emulsions

There was a clear difference between the stability of the LPEs, MPEs and HPEs. Figure 4.1 illustrates the stability of O/W emulsions visually after four weeks. After 2 hours, emulsions 1,3 and 5 were observed to have become unstable. At 12 hours the other emulsions were still stable however after 24 hours emulsions 2,7, 8 and 9 were unstable. At three weeks emulsions 4,6 and 10 were still stable. At four weeks emulsions 4 and 6 were stable but emulsion 10 was unstable with a very small layer of separation at the bottom. Table 4.3 shows the emulsion stability index (ESI). The volume of the bottom layers was measured after four weeks. The HPEs had a high ESI followed by the MPEs then the LPEs. The ESI of the LPEs ranged from 84.0 to 88.0%. Emulsion 5 had the greatest layer of separation at the bottom of the tube hence it had the lowest ESI. All the MPEs had an ESI of 92.0% except for emulsion 7 which had 96.0%. Emulsion 7 had more protein and less water making less it liquidous and as a result had a higher ESI. All HPEs had an ESI of 100% except for emulsion 10 with 99.2% probably the extra 2.22% oil could have caused the instability.

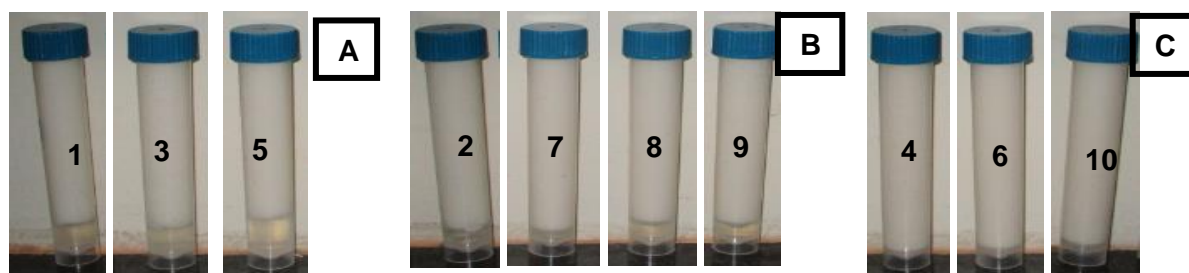


Figure 4.1 O/W Emulsions after four weeks: (A) LPEs: 1 (6% protein, 39% oil, 55% water), 3 (6% protein, 36.26% oil, 57.74% water), 5 (6% protein, 34% oil, 60% water), (B) MPEs: 2 (9.25% protein, 33.25% oil, 57.50% water), 7 (10.50% protein, 34.50% oil, 55% water), 8 (8.14% protein, 36.63% oil, 55.23% water), 9 (10% protein, 30% oil, 60% water), (C) HPEs: 4 (15% protein, 30% oil, 55% water), 6 (12.53% protein, 30% oil, 57.47% water) and 10 (12.78% protein, 32.22% oil, 55% water)

Table 4.3 Emulsion Stability Index

Emulsion Category	Emulsion	Protein%	Oil%	Water%	Emulsion Stability Index (%)
LPEs	1	6.00	39.00	55.00	88.0
	3	6.00	36.26	57.74	88.0
	5	6.00	34.00	60.00	84.0
MPEs	2	9.25	33.25	57.50	92.0
	7	10.50	34.50	55.00	96.0
	8	8.14	36.63	55.23	92.0
	9	10.00	30.00	60.00	92.0
HPEs	4	15.00	30.00	55.00	100.0
	6	12.53	30.00	57.47	100.0
	10	12.78	32.22	55.00	99.2

The stability of the HPEs and the instability of the LPEs that was observed visually was supported by the turbiscan profiles. The variation of thickness of the backscattering graph indicated particle growth or particle migration. The instability mechanisms observed were coalescence and clarification. Coalescence was demonstrated by a horizontal thick line indicating particle growth. Clarification was demonstrated by a vertical thick line indicating particle migration. For the stable emulsions, the backscattering graph showed little or no variation in thickness. The stability tests were conducted to distinguish which composition of emulsions were likely to show which instability phenomenon.

The presence of protein in emulsions introduce a barrier between the oil droplets (Berton-Carabin et al., 2014). The protein is thought to have covered the oil droplets by attaching its lipophilic portion to the droplets and exposing the hydrophilic portions to the water molecules and forming bonds. In this way the water molecules were held together to the oil droplets and repelled from other water molecules and thus maintaining the stability of the emulsions. Interpretations of all O/W emulsions for the stability tests related to the length between 0 and 70 mm of the tube. The LPEs showed instability where both coalescence and clarification occurred as demonstrated in Figure 4.2.

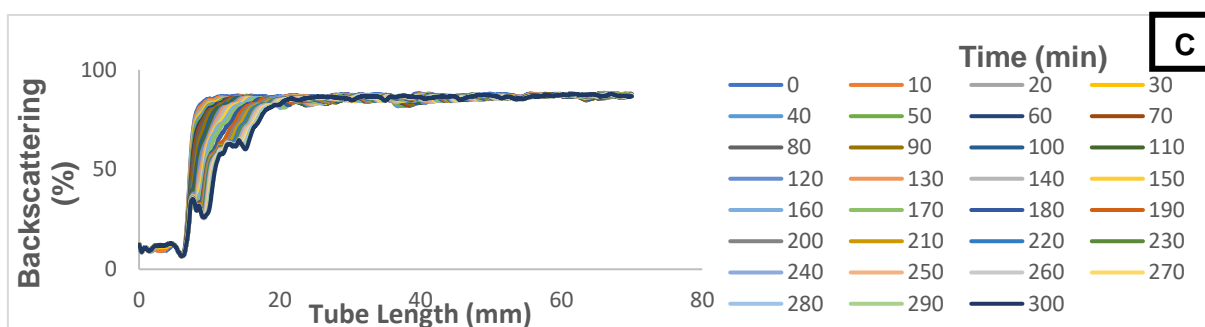
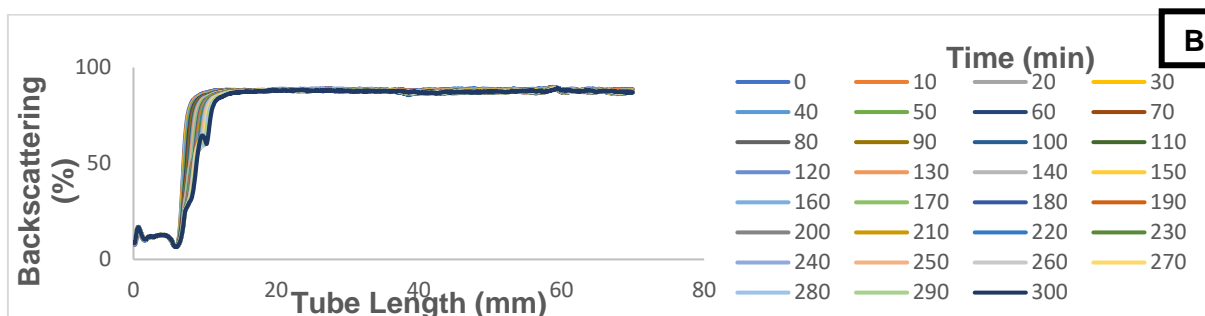
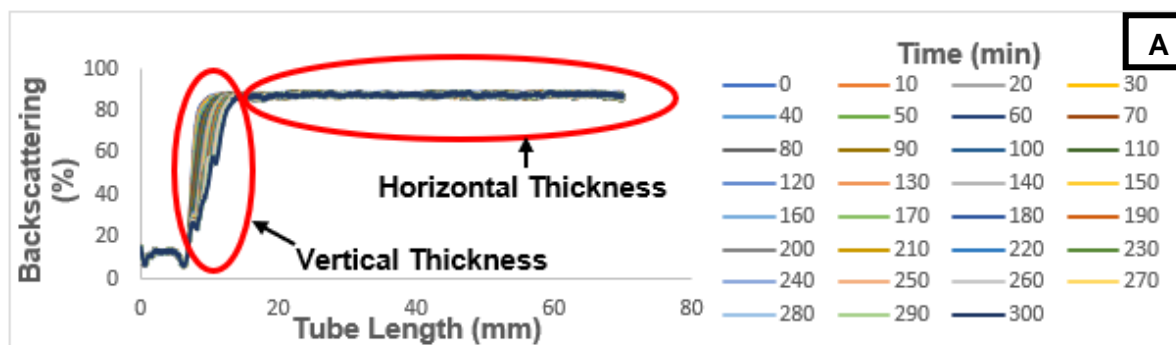


Figure 4.2 Average backscattering profiles of LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water), (B) emulsion 3 (6% protein, 36.26% oil, 57.74% water) and (C) emulsion 5 (6% protein, 34% oil, 60% water)

After scanning the O/W emulsions using a turbiscan, a clear phase was present at the bottom of the tube. The clear layer occurred between 5 to 20 mm from the bottom of the tube. During homogenisation, protein is adsorbed on the surface of the oil droplets (Mccarthy et al., 2015) which prevents the droplets from drawing close to each other and therefore enhancing emulsion stability (Tiwari et al., 2011). As emulsion stability is achieved by oil droplets remaining dispersed in the medium (Zayas, 1997), insufficient protein adsorbed on the oil droplets may encourage the migration of droplets in LPEs.

Visually it was seen that the LPEs were stable for 2 hours. This implies that after a short period, the bonds between the protein and oil and the bonds between the protein and water were not strong enough to overcome the affinity forces of the water molecules and the natural tendency of oil molecules to join again. When protein is added into an emulsion, the structure of the

system changes. Therefore, as more protein is added, more protein-oil bonds are formed such that there are less oil droplets moving thus increasing stability. Protein as an emulsifier holds the water and oil molecules together (Mackey et al., 2017). Therefore, less protein in an emulsion would mean less oil molecules are covered by the protein thus causing separation between the water and oil phases.

In all the LPEs, the movement of droplets could have encouraged collisions which resulted in particle growth. Secondly these emulsions could have had insufficient protein such that some of the droplets were not entirely covered hence not being able to overcome the attraction forces between droplets due to the sites that were not covered by protein therefore causing coalescence to occur. Coalescence was shown by a thick horizontal line from 20 mm of the tube and further up as demonstrated by the backscattering profiles of the LPEs in Figures 4.2 A to 4.2 C. Though the LPEs separated, no complete separation was observed for the 5 hours of scanning, suggesting that regardless of low protein in the emulsions, the BBGN protein isolate was able to hold several oil and water molecules together. Phase separation was evident in the LPEs as demonstrated by a vertical thickness between 5 and 15 mm of the tube length in Figures 4.2 A to 4.2 C.

The phenomena of coalescence in LPEs is also demonstrated through micrographs in Figures 4.3 A, to 4.3 C. These figures indicate non-uniform droplet sizes which would have been caused by some of the droplets joining and growing. Emulsions 1, 3 and 5 had droplets clustered together which could be due to insufficient protein adsorbed on the droplets therefore coalescence being encouraged to occur. The images demonstrate protein surrounding the droplets by the dark lining at the outer edge of droplets. For emulsion 1,3 and 5 there were also small droplets present as well; this could be due to protein surrounding the droplets creating a boundary strong enough to resist the droplets from flocculating.

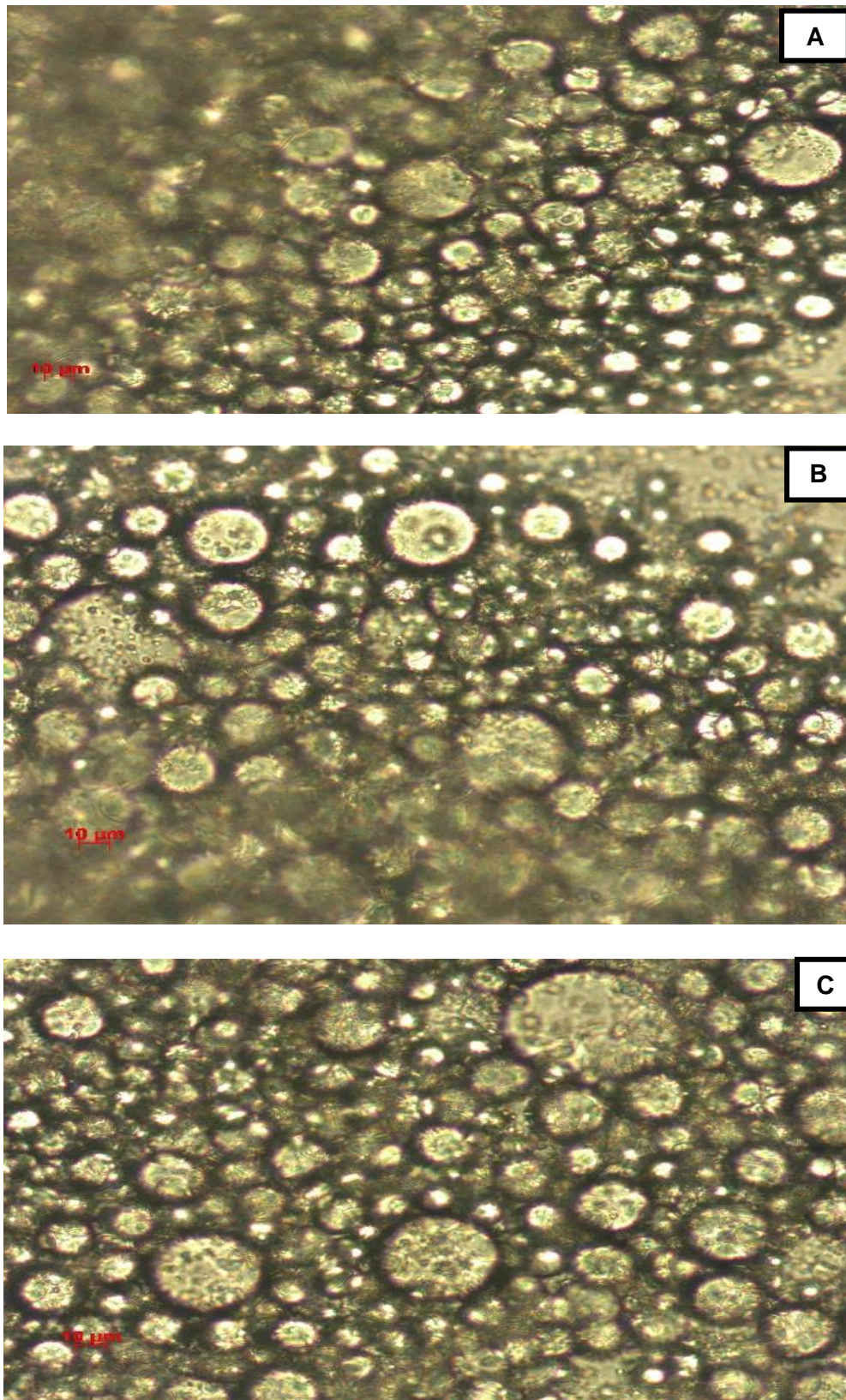


Figure 4.3 Micrographs for LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water), (B) emulsion 3 (6% protein, 36.26% oil, 57.74% water) and (C) emulsion 5 (6% protein, 34% oil, 60% water)

For the MPEs, there was no phase separation for 5 hours as little or no vertical thickness occurred as shown in Figures 4.4 and 4.5 unlike that of the LPEs illustrating that the protein molecules available were able to prevent the molecules from migrating.

There was no detection of coalescence for the MPEs during the 5 hours of turbiscan analysis, however, for emulsion 9, coalescence took place as demonstrated by a thick horizontal line in Figure 4.5. Coalescence could have happened as a result of oil molecules not entirely covered by the protein. Therefore, there could have been few oil molecules that did not have sufficient protein adsorbed on their surfaces however not as much as those of the LPEs.

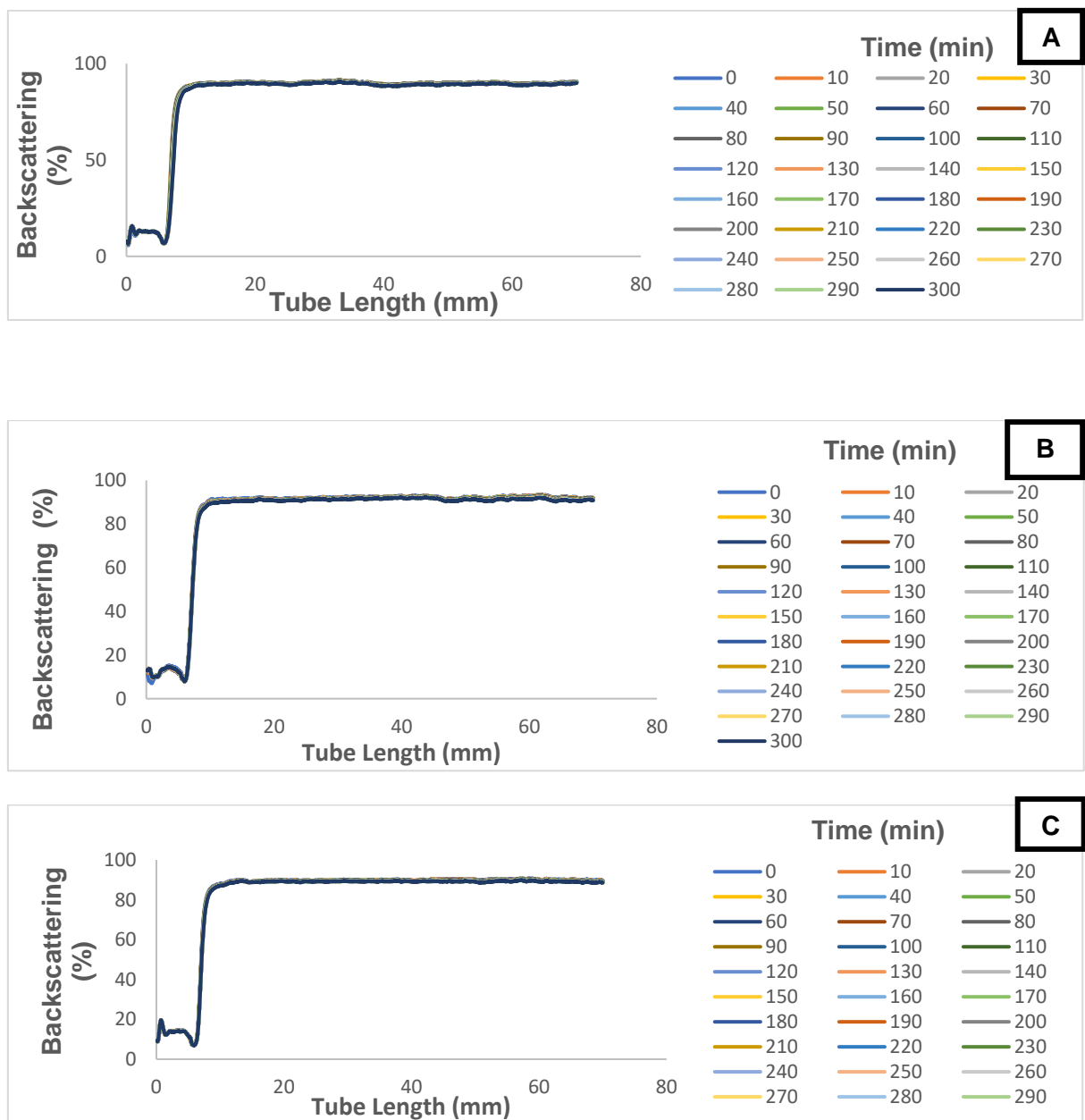


Figure 4.4 Average backscattering profiles of MPEs: (A) emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), (B), emulsion 7 (10.50% protein, 34.50% oil, 55% water) and (C) emulsion 8 (8.14% protein, 36.63% oil 55.23% water)

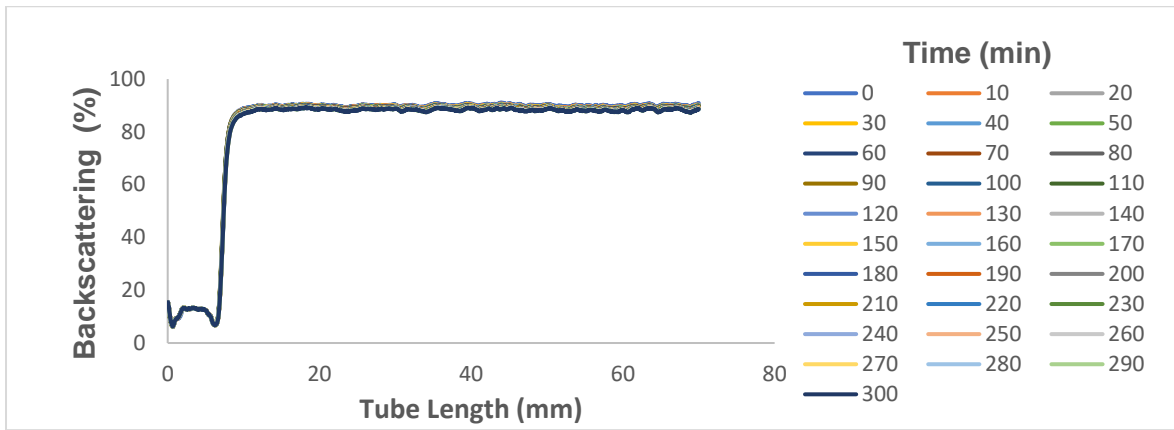


Figure 4.5 Average backscattering profiles of MPE: emulsion 9 (10% protein, 30% oil, 60% water)

The droplet sizes of the MPEs were more uniform than those of the LPEs. Some of the droplet sizes of the MPEs (for example emulsion 9 shown in Figure 4.7 C) were not completely uniform however they were not as diverse as those of the LPEs. The dark shade on some of the micrographs are due to the thickness of the emulsions which was challenging to capture images on a single layer of the emulsion.

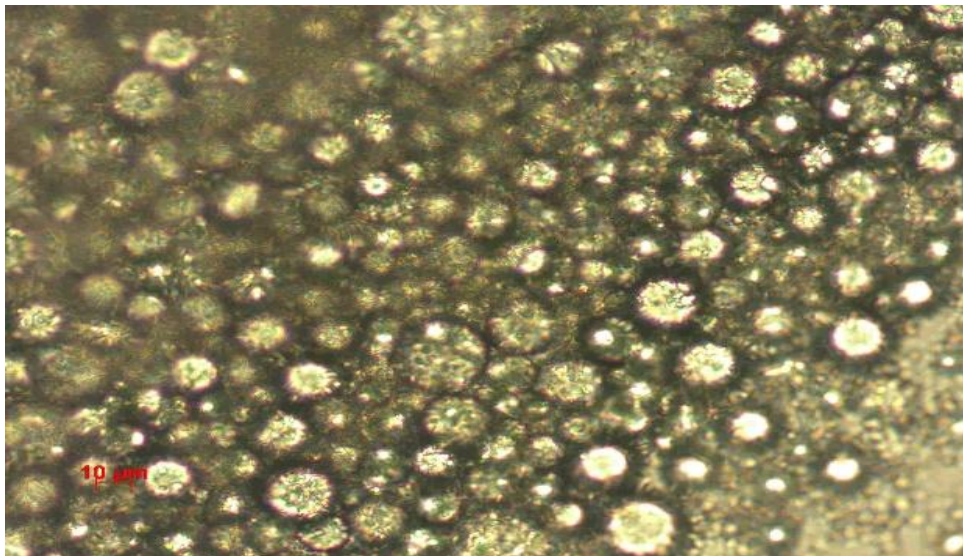


Figure 4.6 Micrographs for MPE: emulsion 2 (9.25% protein, 33.25% oil, 57.50% water)

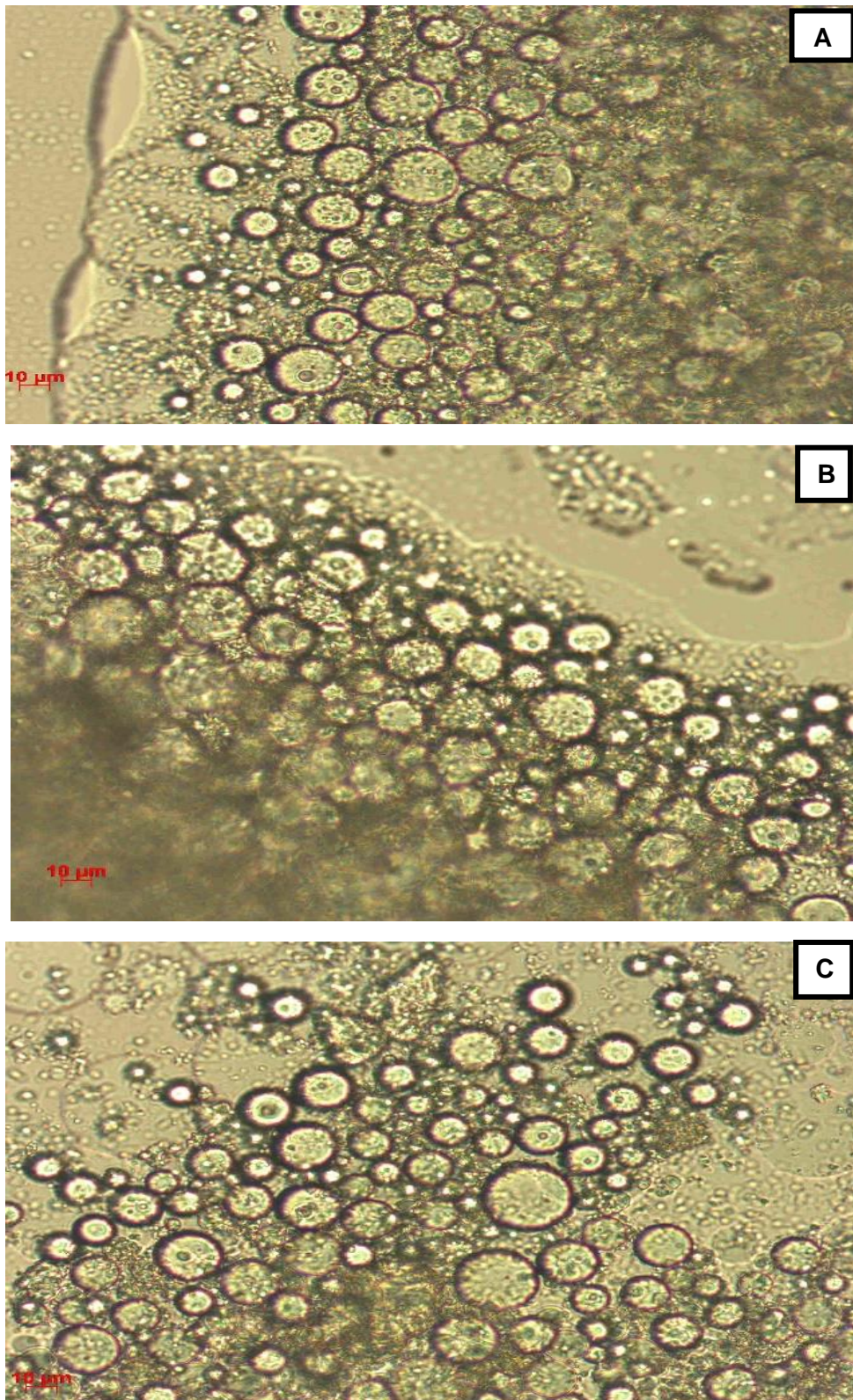


Figure 4.7 Micrographs for MPEs: (A) emulsion 7 (10.50% protein, 34.50% oil, 55% water), (B) emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and (C) emulsion 9 (10% protein, 30% oil, 60% water)

The HPEs (4, 6 and 10) were stable as demonstrated by a thin line between 10 and 70 mm as shown in Figures 4.8 A, 4.8 B and 4.9. All the HPEs did not show vertical thickness like that of the LPEs as indicated in Figures 4.2 A to 4.2 C. Figure 4.9 shows slight variation of the horizontal line for emulsion 10 (12.78% protein, 32.22% oil, 55% water). This was not expected as it was a HPE however this may have occurred due to the extra oil. As more protein was present in the HPEs could imply that more protein-oil bonds were formed between and causing the majority of the oil droplets to be covered. This could suggest that in order to destabilise these emulsions an external or internal greater force would be required to break the barriers and weaken the bonds and separate the oil and water molecules. These forces could be induced by pH (Gupta and Ghosh, 2015), temperature, stress (Zayas, 1997) and bacterial growth (Moynihan, 2009). The thickness of the HPEs could be due to more molecules that are congested or tightly packed (Bullinger, 2009) (however not flocculating due to the strong protein interfacial film) and as a result not free to move about (Pycia et al., 2018) thus suggesting a more uniform structure (indicating stability) (Kobayashi et al., 2009) than the LPEs.

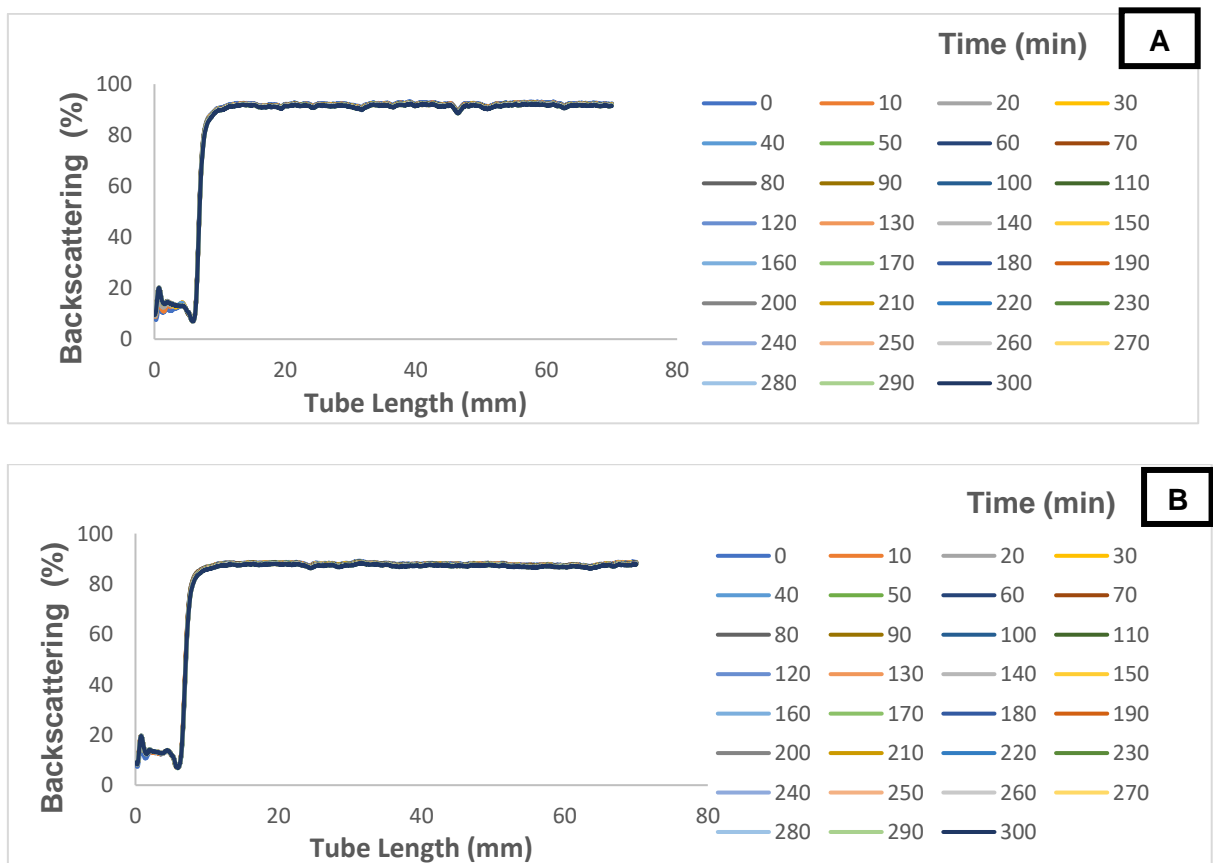


Figure 4.8 Average backscattering profiles of HPEs: (A) emulsion 4 (15% protein, 30% oil, 55% water) and (B) emulsion 6 (12.53% protein, 30% oil, 57.47% water)

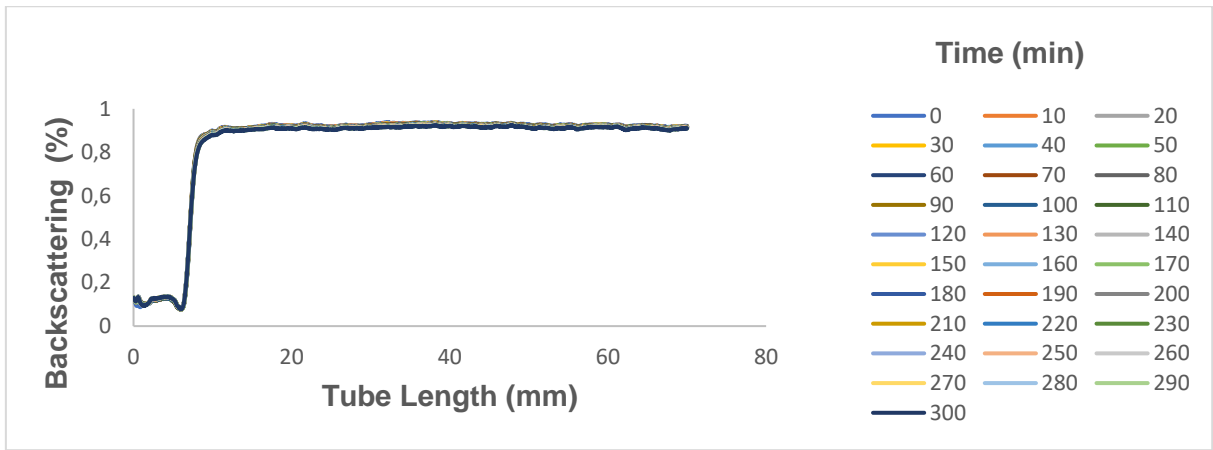


Figure 4.9 Average backscattering profile of HPE: emulsion 10 (12.78% protein, 32.22% oil, 55% water)

The micrographs of the HPEs confirmed their stability. The thick emulsions (HPEs) had more uniform droplet sizes as compared to the liquid-like emulsions (LPEs) for example as seen in Figures 4.10, 4.11 A and 4.11 B representing emulsions 4,6 and 10, respectively. Their droplets were more dispersed and not as clustered as those of the LPEs hence that did not encourage coalescence to occur.

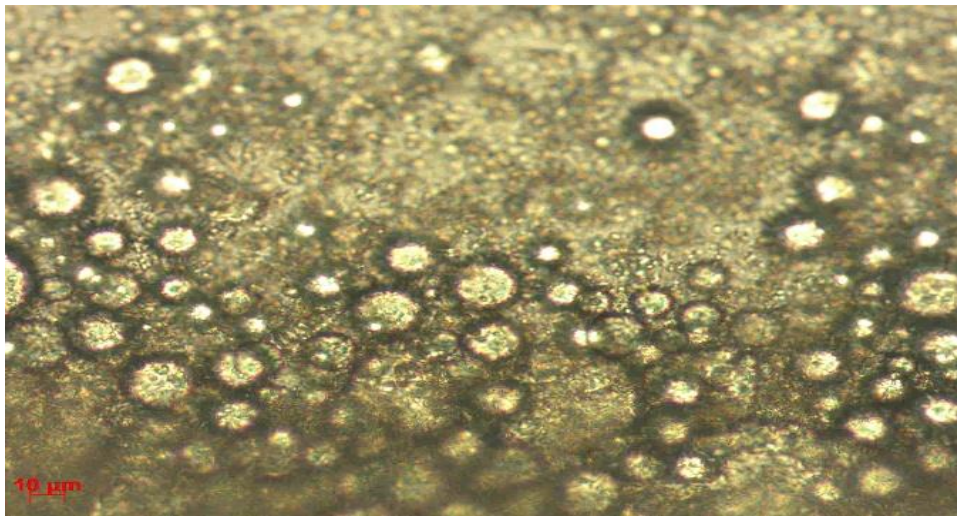


Figure 4.10 Micrograph for HPE: emulsion 4 (15% protein, 30% oil, 55% water)

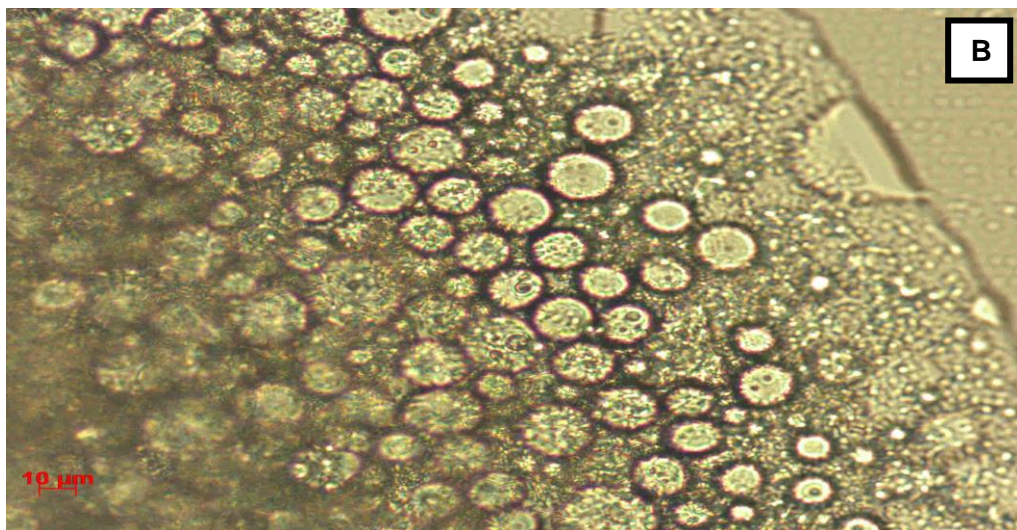
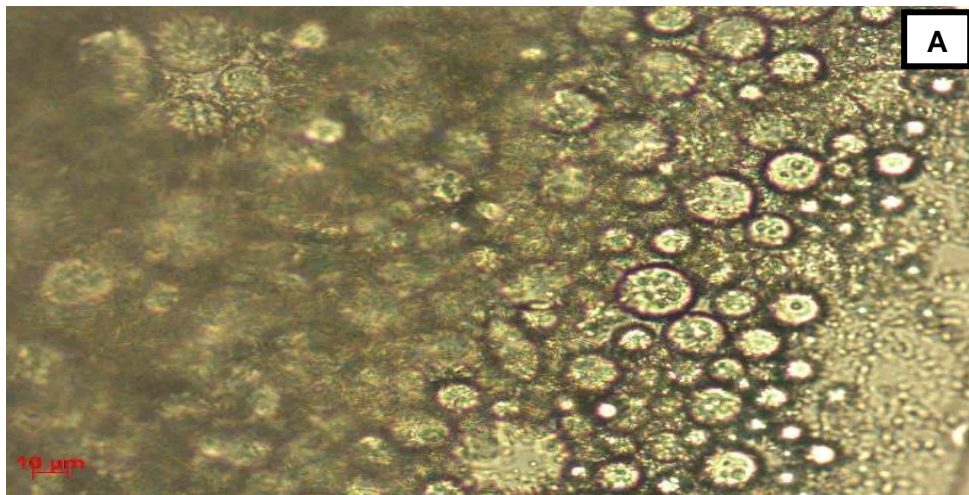


Figure 4.11 Micrographs for HPEs: (A) emulsion 6 (12.53% protein, 30% oil, 57.47% water) and (B) emulsion 10 (12.78% protein, 32.22% oil, 55% water)

4.4 Modelling the Effect of Protein, Oil and Water on the Migration Rate and Turbiscan Stability Index (TSI) of the O/W Emulsions using Mixture Model

The migration rate and TSI data for each emulsion is presented in Table 4.4 which differentiates the stability properties from the low to the high protein emulsions.

Table 4.4 Migration Rate and Turbiscan Stability Index of O/W Emulsions

					Migration	
					Rate	
Emulsion					(mm/min)	TSI
Category	Emulsion	Protein %	Oil %	Water %		
LPEs	1	6.00	39.00	55.00	1.20×10^{-2}	9.27×10^{-3}
	3	6.00	36.26	57.74	9.10×10^{-3}	7.89×10^{-3}
	5	6.00	34.00	60.00	2.53×10^{-2}	1.64×10^{-2}
MPEs	2	9.25	33.25	57.50	1.07×10^{-3}	2.36×10^{-3}
	7	10.50	34.50	55.00	8.50×10^{-5}	2.61×10^{-3}
	8	8.14	36.63	55.23	2.00×10^{-4}	2.47×10^{-3}
	9	10.00	30.00	60.00	1.50×10^{-4}	4.24×10^{-3}
HPEs	4	15.00	30.00	55.00	5.50×10^{-5}	1.71×10^{-3}
	6	12.53	30.00	57.47	6.00×10^{-5}	2.19×10^{-3}
	10	12.78	32.22	55.00	2.00×10^{-5}	3.35×10^{-3}

The LPEs had the highest migration rate ranging from 9.10×10^{-3} to 2.53×10^{-2} mm/min. Emulsion 5 (6% protein, 34% oil, 60% water) had a migration rate of 2.53×10^{-2} mm/min as it was the least viscous indicating to have been more mobile as demonstrated by the greatest variation of the backscattering graph in Figure 4.2C. All MPEs had migration rates (8.50×10^{-5} to 1.07×10^{-3} mm/min) which were higher than the HPEs. Emulsion 10 had the least migration rate among the HPEs. The LPEs had the highest TSI followed by the MPEs then the HPEs. However, emulsion 10 had a higher TSI than most of the MPEs. As emulsion 10 had a thick horizontal variation (coalescence) (Figure 4.9) due to extra oil, the TSI was higher than expected.

4.4.1 Adequacy of mixture model

The quadratic and linear mixture model was sufficient to explain the variation of the migration rate and TSI, respectively in the O/W emulsions. The measure of the significance of the models is described in Tables 4.5 and 4.6 which represents the ANOVA for the quadratic and linear mixture model respectively.

There was a significant relationship between migration rate and emulsion composition since the obtained p-value was 0.0014 which was less than 0.05. Significant ($p = 0.0069$) quadratic effect existed between protein, oil. The lack of fit ($p = 0.7667$) was not significant indicating that the quadratic mixture model explained the variation in the data.

The linear mixture model significantly ($p = 0.0012$) explained the variation in TSI. The p-value demonstrated that there was a 0.12% chance of an error that could have occurred perhaps due to both experimental and human error. It further demonstrated that there was a 99.88% chance that the variation in TSI could have occurred due to the changes in protein/oil/water composition, which is good. The lack of fit ($p = 0.0951$) indicates that the linear mixture model explained the variation in the TSI due to the emulsion composition. The quadratic and linear mixture design could be used to navigate the design space for migration rate and TSI, respectively.

Table 4.5 ANOVA for Quadratic Mixture Model for Migration Rate

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	54.74	5	10.95	14.47	0.0014	significant
¹ Linear Mixture	42.95	2	21.47	28.38	0.0004	
AB	10.78	1	10.78	14.25	0.0069	
AC	0.012	1	0.012	0.016	0.9026	
BC	0.39	1	0.39	0.52	0.4947	
Residual	5.30	7	0.76			
Lack of Fit	1.20	3	0.40	0.39	0.7667	not significant
Pure Error	4.10	4	1.02			
Cor Total	60.03	12				

A= Protein (%), B= Oil (%), C= Water (%)

Table 4.6 ANOVA for Linear Mixture Model for TSI

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	252.75	2	126.38	13.18	0.0012	significant
<i>¹Linear Mixture</i>	<i>252.75</i>	<i>2</i>	<i>126.38</i>	<i>13.18</i>	<i>0.0012</i>	
Residual	105.44	11	9.59			
<i>Lack of Fit</i>	<i>92.57</i>	<i>7</i>	<i>13.22</i>	<i>4.11</i>	<i>0.0951</i>	<i>not significant</i>
<i>Pure Error</i>	<i>12.87</i>	<i>4</i>	<i>3.22</i>			
Cor Total	358.20	13				

4.4.2 Effect of protein, oil and water on migration rate and TSI

Figures 4.12 and 4.13 graphically describes the effect of the protein/oil/water composition on the migration rate and the TSI, respectively. Figure 4.12 demonstrates that as protein was increased the migration rate decreased. This trend was observed between the LPEs and HPEs. The presence of protein between oil droplets keeps them dispersed in the water as the medium. The adsorption of protein on the surface of the oil droplets does not encourage their movement and therefore the migration rate would decrease. When the oil was increased while the protein is decreased, the protein became insufficient to keep the oil molecules apart and maintaining the thickness of the emulsion, hence the migration rate increased. Sun and Gunasekaran (2009) investigated the effect of protein concentration and oil-phase volume fraction on the stability and rheology of O/W emulsions stabilised by whey protein. The study concluded that increasing the protein concentration slightly decreased the creaming rate. Though there was a decrease in the creaming rate, unadsorbed whey protein in the external phase could have lowered the creaming rate. This study observed that the migration rate of the LPEs was higher than that of the HPEs implying that creaming rate was lower for the HPEs compared to the LPEs. The findings of this study were similar to that of Sun and Gunasekaran (2009) however the difference was the amount of protein used. The range of protein concentration in the study of Sun and Gunasekaran (2009) was between 0.2 to 2 wt % and perhaps the amount of protein was not as high to cause a greater decrease of the creaming rate.

More protein stabilises an emulsion hence a turbiscan profile would indicate less variation in the backscattering intensity or the graph would be less thick leading to a lower TSI. Figure 4.13 demonstrates that the TSI was increased by the increase of oil and water concentration and the decrease in protein concentration. Increasing oil and water while decreasing protein, increased the liquid portion of the emulsion which encouraged movement of particles from one location to another. This movement was shown by the variation in the backscattering graphs

which resulted in the increase of TSI. Formulation (2014) studied the effect of pea protein on emulsion stability and reported that increasing pea protein reduces the TSI thus demonstrating an increase in emulsion stability. In this study it was observed that the HPEs had lower migration rate and TSI values than those of the LPEs. However, there was no clear trend between the HPEs and MPEs.

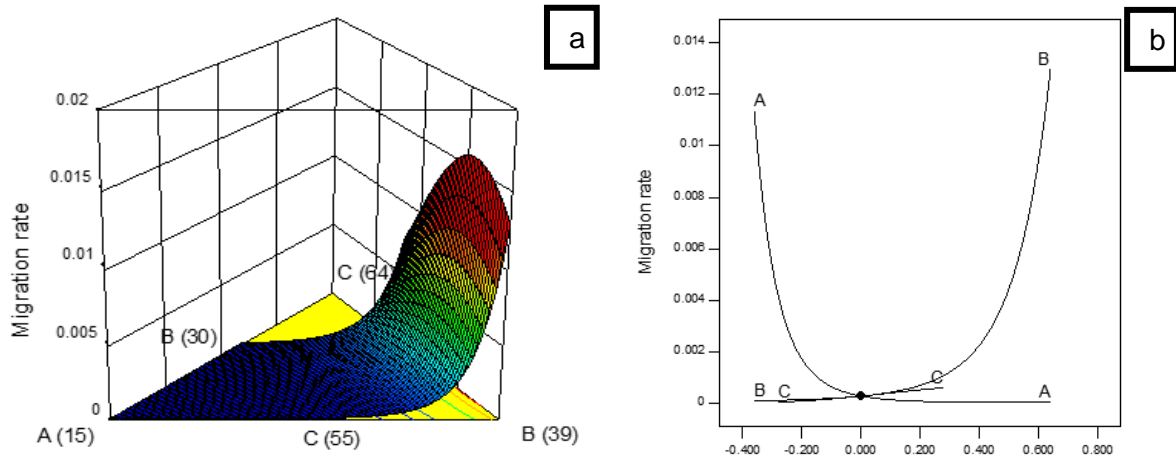


Figure 4.12 Relationship between emulsion composition and migration rate (A= Protein (%), B= Oil (%), C= Water (%)) (a) 3-D response surface and (b) trace plot

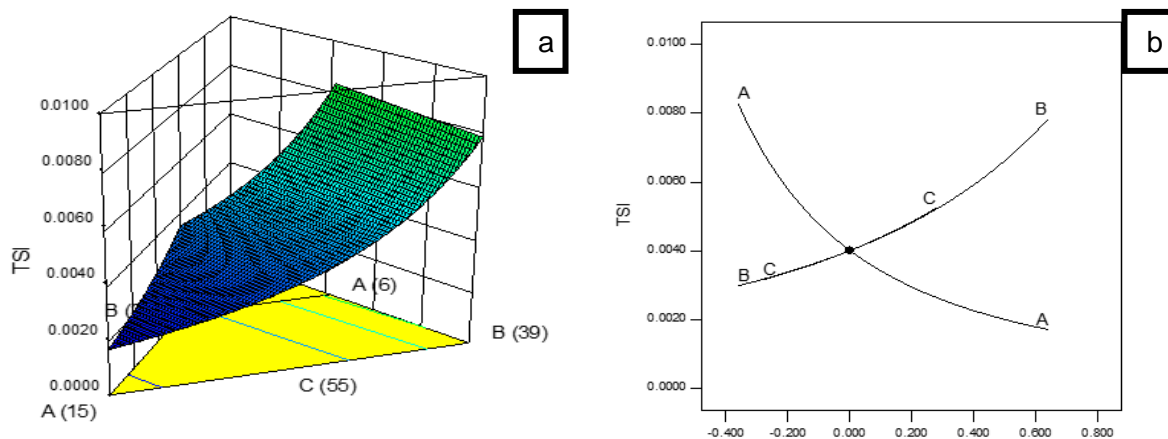


Figure 4.13 Relationship between emulsion composition and TSI (A= Protein (%), B= Oil (%), C= Water (%)) (a) 3-D response surface and (b) trace plot

Based on the goal of minimising the migration rate and the TSI, the emulsion combination (15% protein, 30% oil, 55% water) was the selected optimum with a desirability of 0.997. The emulsion with this combination was observed to be stable after four weeks (Figure 4.1).

4.5 Effect of Protein, Oil and Water on the Viscosity of O/W Emulsions

The rotational steady state tests mimics and demonstrated how speed during an industrial situation of mixing, pouring and pumping can affect the quality of the emulsions. Figures 4.14 to 4.17 illustrate the behaviour of the emulsion's viscosity with the change in shear rate and

Table 4.7 illustrate the viscosity of emulsions at the lowest shear rate of 0.01 s^{-1} at which the least structural disturbance occurs.

At a shear rate of 0.01 s^{-1} , increasing protein concentration increased the viscosity as shown in Table 4.7 except for emulsion 8 (8.14% protein, 36.63% oil 55.23% water), which did not follow this trend. Though emulsion 8 had the least amount of protein amongst the MPEs, perhaps due to a greater amount of oil content resulted in a higher viscosity than most of the MPEs. Iqbal et al. (2017) investigated how egg white protein affects the stability of O/W emulsions and concluded that the increase in protein concentration increased emulsion viscosity which is a similar trend to this study at a shear rate of 0.01 s^{-1} . However, as the shear rate increased for the LPEs, MPEs and HPEs, this trend was not applicable as the flow curves started overlapping indicating that the emulsions that had a higher viscosity at a shear rate of 0.01 s^{-1} , did not remain high throughout the shear rate range. The overlapping of the flow curves in each category could be due to the difference in the interaction of the protein, oil and water (inconsistency of desorption of protein) as the shear rate increased as the oil and water composition was not the same for all emulsions. Secondly, though the compositions of the emulsions were not the same, the composition of the protein in each category was close to each other and as a result having overlapping of the flow curves. Lastly, it could indicate that as the shear rate was increased the protein did not affect the viscosity significantly.

All emulsions had shear thinning as demonstrated by the decrease in viscosity with the increase in shear rate which is caused by the weakening of bonds. Shear thinning was also observed in the study conducted by Iqbal et al. (2017). The LPEs were liquid like with the lowest viscosity ranging from 33.91 to 90.93 Pa.s at a shear rate of 0.01 s^{-1} . Though all LPEs had 6% protein concentration, they did not have the same viscosity since their water and oil concentration were not the same. For example, between emulsion 1 (6% protein 39% oil and 55% water) and emulsion 5 (6% protein, 34% oil and 60% water), emulsion 5 was less viscous with a viscosity of 33.91 Pa.s while emulsion 1 had a viscosity of 80.93 Pa.s at a shear rate of 0.01 s^{-1} . More water content could have made emulsion 5 less viscous while more oil in emulsion 1 could have increased the viscosity. The viscosity of the MPEs was higher than that of the LPEs and ranged from 109.61 to 158.80 Pa.s at a shear rate of 0.01 s^{-1} . The viscosity of the HPEs ranged from 215.23 to 232.33 Pa.s at a shear rate of 0.01 s^{-1} . Emulsion 4 (15% protein, 30% oil, 55% water) had the highest viscosity of 232.33 Pa.s at a shear rate of 0.01 s^{-1} which was expected as this emulsion contained the highest protein content. At a shear rate of 0.4, 0.6 and 0.6 s^{-1} for the LPEs, MPEs and HPEs respectively, the viscosity curves become constant indicating infinite shear rate viscosity (Gaonkar, 1995).

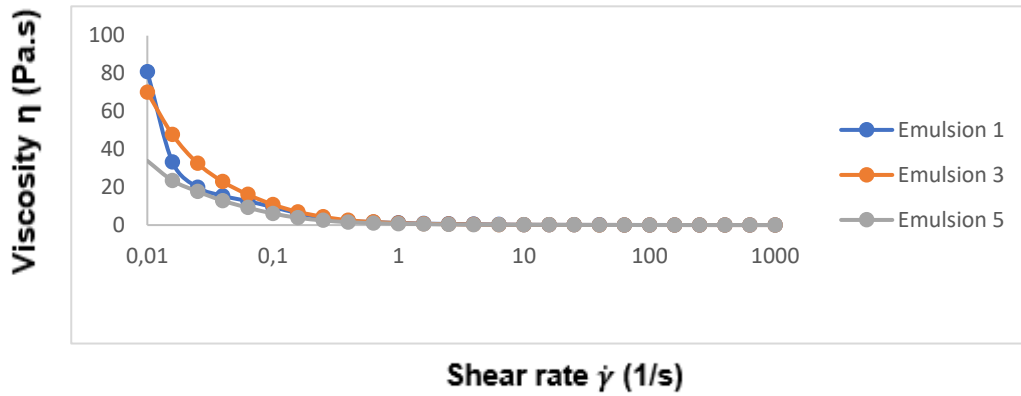


Figure 4.14 The relationship between viscosity and shear rate for LPEs: emulsion 1 (6% protein, 39% oil, 55% water), emulsion 3 (6% protein, 36.26% oil, 57.74% water) and emulsion 5 (6% protein, 34% oil, 60% water)

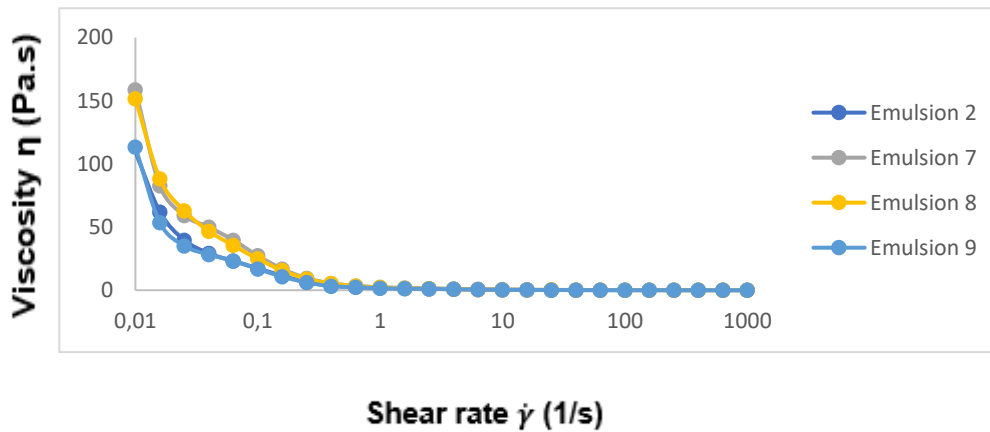


Figure 4.15 The relationship between viscosity and shear rate for MPEs: emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), emulsion 7 (10.50% protein, 34.50% oil, 55% water), emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and emulsion 9 (10% protein, 30% oil, 60% water)

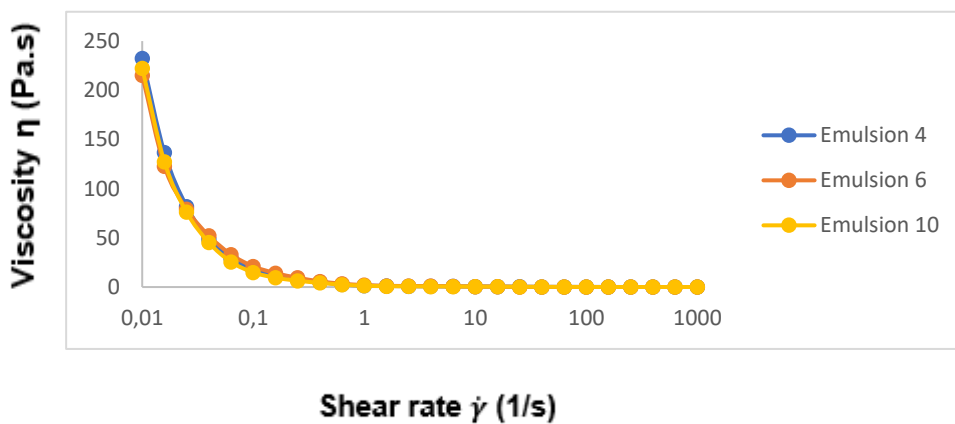


Figure 4.16 The relationship between viscosity and shear rate for HPEs: emulsion 4 (15% protein, 30% oil, 55% water), emulsion 6 (12.53% protein, 30% oil, 57.47% water) and emulsion 10 (12.78% protein, 32.22% oil, 55% water)

Figure 4.17 shows the flow curves of emulsions 1, 7 and 4 as an example to illustrate the variation of viscosity between the LPE, MPE and HPE respectively. There is a clear variation between the viscosity of emulsion 1 and emulsion 4 throughout the shear rate range. From 0.1 s⁻¹ the variation is not shown clearly but emulsion 4 had a greater viscosity than emulsion 1 as shown in Tables B4 and B1 in Appendix B respectively. Emulsion 7 and 4 shows overlapping. Emulsion 7 was a MPE due to arbitrary classification of emulsions and probably could have behaved as a HPE in this case.

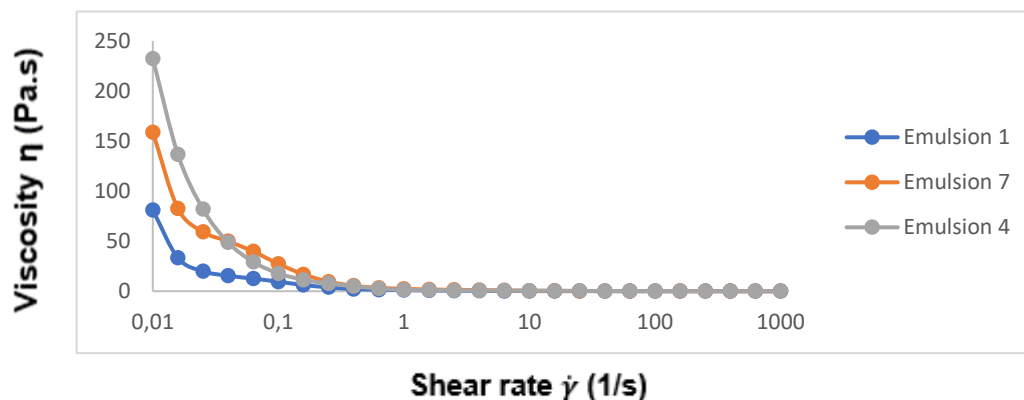


Figure 4.17 The relationship between viscosity and shear rate for emulsion 1 (LPE) (6% protein, 39% oil, 55% water), emulsion 7 (MPE) (10.50% protein, 34.50% oil, 55% water) and emulsion 4 (HPE) (15% protein, 30% oil, 55% water)

Table 4.7 Viscosity of O/W Emulsions

Emulsion	Category	Emulsion	Protein %	Oil %	Water %	Average Viscosity ¹
HPEs		4	15.00	30.00	55.00	232.33
		10	12.78	32.22	55.00	222.39
		6	12.53	30.00	57.47	215.23
MPEs		7	10.50	34.50	55.00	158.80
		8	8.14	36.63	55.23	151.52
		9	10.00	30.00	60.00	113.27
		2	9.25	33.25	57.50	109.61
LPEs		1	6.00	39.00	55.00	80.93
		3	6.00	36.26	57.74	70.07
		5	6.00	34.00	60.00	33.91

¹ At beginning of test (shear rate of 0.01 s⁻¹) in descending order (Pa.s)

Emulsions 7 (10.50% protein, 34.50% oil and 55.23% water) and 10 (12.78% protein, 32.22% oil and 55% water) had similar amount of water content, however emulsion 7 was less viscous than emulsion 10 due to less protein content though it had a higher oil content. Having less protein would mean that there would be extra oil droplets not having protein adsorbed on it and thus inducing less repulsive forces between the oil droplets.

4.5.1 Flow behaviour of O/W emulsions as described by different models

The model parameters of the Power Law, Herschel- Bulkley, Bingham and Casson models are described in Tables 4.8, 4.9, 4.10 and 4.11, respectively. All emulsions experienced shear thinning as n (flow behaviour index) demonstrated by both the Power Law and Herschel-Bulkley models, was less than 1. All emulsions had yield stress. According to the Bingham model, the HPEs had a higher yield stress (3.24 to 4.02 Pa) followed by the MPEs (2.35 to 3.93 Pa) then the LPEs (1.02 to 1.48 Pa). According to the Casson model, the yield stress of the HPEs (1.82 to 2.26 Pa) was also higher than that of the MPEs (1.04 to 1.95 Pa) followed by the LPEs (0.06 to 0.71 Pa). However, emulsion 7 which was a MPE had a yield stress of 3.93 and 1.95 Pa as given by the Bingham and Casson models, respectively which was in the range of that of the HPEs probably due to arbitrary classification as discussed previously. The Hershel-Bulkley model demonstrated that all emulsions had yield stress however there was no particular trend observed.

The Casson viscosity as shown in Table 4.11 was greater than the Bingham viscosity (Table 4.10) for all emulsions. As the HPEs were more viscous than the MPEs followed by the LPEs, it was expected that the consistency coefficient would decrease in that order. This trend was demonstrated by the consistency coefficient of both the Power Law and Herschel-Bulkley models. According to the Power Law, the HPEs had a higher consistency coefficient of 2.02 to 2.48 Pa.s ^{n} followed by that of the MPEs (0.97 to 0.98 Pa s ^{n}) then the LPEs (0.26 to 0.60 Pa s ^{n}). For the Herschel- Bulkley model, the HPEs had a high consistency coefficient of 1.14 to 1.65 Pa s ^{n} followed by that of the MPEs (0.31 to 0.80 Pa s ^{n}) then the LPEs (0.15 to 0.20 Pa s ^{n}).

The best fit model for all emulsions was the Hershel-Bulkley model except for emulsion 7. Data fitted using the Hershel-Bulkley model had the lowest RMSE and SSE with the highest adjusted R² compared to those of the Power Law, Bingham and Casson models. The Casson model was the best fit model for emulsion 7 as the RMSE and SSE were the lowest and having the highest adjusted R² compared to those of the Power Law, Bingham and Hershel- Bulkley models. According to Izidoro et al. (2009), the Power Law, Herschel- Bulkley and Casson models are used to describe the flow properties of emulsions such as mayonnaise and salad dressing. Therefore, emulsions in this study resemble some properties of either mayonnaise and salad dressing as the Herschel-Bulkley model was the best fit model except for emulsion 7.

Table 4.8 Power Law Model Parameters

Emulsion										
Category	Emulsion	Protein %	Oil %	Water %	n	k (Pa.s ⁿ)	R ²	Adjusted R ²	SSE	RMSE
LPEs	1	6.00	39.00	55.00	0.5704	0.3889	0.9864	0.9858	8.648	0.6003
	3	6.00	36.26	57.74	0.4014	0.5955	0.9476	0.9454	7.925	0.5746
	5	6.00	34.00	60.00	0.5897	0.2585	0.9905	0.9901	3.466	0.3800
MPEs	2	9.25	33.25	57.50	0.3735	1.4400	0.9795	0.9786	13.120	0.7394
	7	10.50	34.50	55.00	0.3822	1.9960	0.9724	0.9713	37.870	1.2560
	8	8.14	36.63	55.23	0.3673	1.6710	0.9659	0.9645	26.240	1.0460
	9	10.00	30.00	60.00	0.4367	0.9564	0.9650	0.9636	22.380	0.9656
HPEs	4	15.00	30.00	55.00	0.3294	2.4800	0.9776	0.9766	24.600	1.0120
	6	12.53	30.00	57.47	0.3251	2.4810	0.9764	0.9754	23.770	0.9952
	10	12.78	32.22	55.00	0.3221	2.0220	0.9699	0.9687	19.550	0.9025

Table 4.9 Herschel-Bulkley Model Parameters

Emulsion		Adjusted R ²									
Category	Emulsion	Protein %	Oil %	Water %	n	k (Pa.s ⁿ)	τ (Pa)	R ²	SSE	RMSE	
LPEs	1	6.00	39.00	55.00	0.6658	0.1986	0.8061	0.9986	0.9985	0.9055	0.1984
	3	6.00	36.26	57.74	0.5975	0.1517	0.9023	0.9947	0.9942	0.8071	0.1873
	5	6.00	34.00	60.00	0.6717	0.1450	0.5193	0.9995	0.9994	0.1919	0.0913
MPEs	2	9.25	33.25	57.50	0.4840	0.6605	1.2680	0.9964	0.9961	2.3030	0.3164
	7	10.50	34.50	55.00	0.5136	0.7951	2.0440	0.9939	0.9934	8.3460	0.6024
	8	8.14	36.63	55.23	0.5222	0.5639	1.8500	0.9979	0.9978	1.5820	0.2622
	9	10.00	30.00	60.00	0.5979	0.3112	1.4460	0.9943	0.9938	3.6710	0.3995
HPEs	4	15.00	30.00	55.00	0.3855	1.6520	1.1130	0.9831	0.9817	18.5000	0.8968
	6	12.53	30.00	57.47	0.4185	1.2740	1.6240	0.9897	0.9888	10.3900	0.6723
	10	12.78	32.22	55.00	0.4018	1.1400	1.1800	0.9806	0.9790	12.5800	0.7397

Table 4.10 Bingham Model Parameters

Emulsion										
Category	Emulsion	Protein %	Oil %	Water %	η (Pa.s)	τ (Pa)	R ²	Adjusted R ²	SSE	RMSE
LPEs	1	6.00	39.00	55.00	0.02107	1.484	0.9630	0.9615	23.520	0.9900
	3	6.00	36.26	57.74	0.01016	1.346	0.9419	0.9395	8.783	0.6049
	5	6.00	34.00	60.00	0.01602	1.019	0.9659	0.9645	12.490	0.7214
MPEs	2	9.25	33.25	57.50	0.0204	2.732	0.8968	0.8925	66.090	1.6590
	7	10.50	34.50	55.00	0.03018	3.931	0.9143	0.9107	117.700	2.2150
	8	8.14	36.63	55.23	0.02262	3.226	0.9151	0.9116	65.410	1.6510
	9	10.00	30.00	60.00	0.02093	2.354	0.9441	0.9418	35.740	1.2200
HPEs	4	15.00	30.00	55.00	0.02557	3.992	0.8230	0.8156	194.000	2.8430
	6	12.53	30.00	57.47	0.02503	4.017	0.8588	0.8529	142.100	2.4330
	10	12.78	32.22	55.00	0.01985	3.240	0.8360	0.8291	106.600	2.1080

Table 4.11 Casson Model Parameters

Emulsion										
Category	Emulsion	Protein %	Oil %	Water %	η (Pa.s)	τ (Pa)	R ²	Adjusted R ²	SSE	RMSE
LPEs	1	6.00	39.00	55.00	0.5882	0.21010	0.9821	0.9813	11.410	0.6895
	3	6.00	36.26	57.74	0.2877	0.70800	0.9885	0.9881	1.734	0.2688
	5	6.00	34.00	60.00	0.4464	0.05545	0.9820	0.9813	6.581	0.5237
MPEs	2	9.25	33.25	57.50	0.5944	1.35200	0.9962	0.9961	2.424	0.3178
	7	10.50	34.50	55.00	0.8698	1.94600	0.9938	0.9935	8.518	0.5957
	8	8.14	36.63	55.23	0.6526	1.73300	0.9976	0.9975	1.855	0.2780
	9	10.00	30.00	60.00	0.5920	1.04400	0.9886	0.9881	7.326	0.5525
HPEs	4	15.00	30.00	55.00	0.7677	2.12900	0.9710	0.9698	31.800	1.1510
	6	12.53	30.00	57.47	0.7407	2.25600	0.9842	0.9835	15.910	0.8141
	10	12.78	32.22	55.00	0.5917	1.81900	0.9721	0.9709	18.150	0.8696

4.6 Viscoelastic Properties of O/W Emulsions

This section presents the response of O/W emulsions at different strains, frequency, temperature and time.

4.6.1 Effect of strain on the viscoelastic properties of O/W emulsions

The test was performed to compare at which strains do the emulsions of different compositions remain stable as represented by the linear viscoelastic region and this section describes the reasons of the emulsion's linearity occurring at particular strains. This test was performed to analyse the emulsion's structural strength and to determine the occurrences of phase changes (which is the point where $G' = G''$). Figures 4.18 to 4.20 describes the behaviour of the storage and loss modulus over a strain range. The linear viscoelastic region (LVR) showed the stability of the O/W emulsions. All emulsions initially had a LVR and at a particular point both G' and G'' deviated and decreased until they crossed except for some of the LPEs which did not cross.

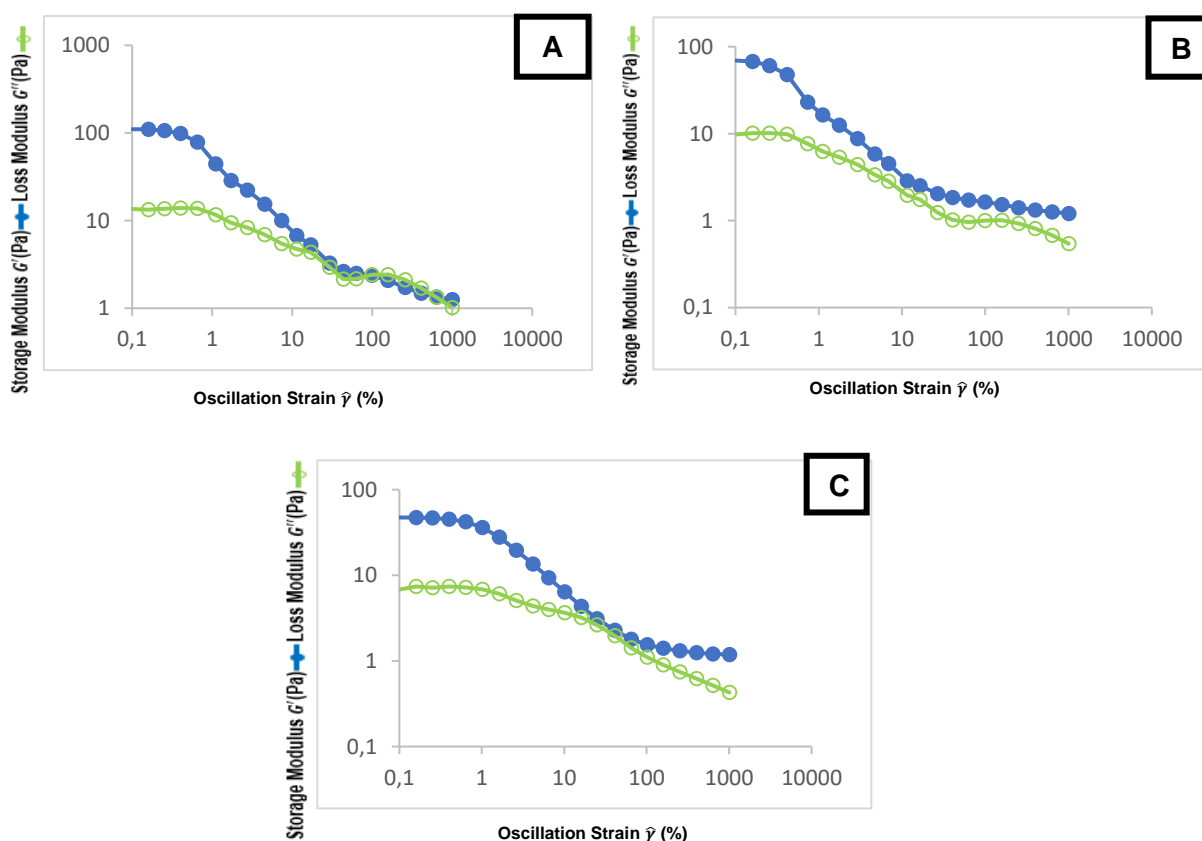


Figure 4.18 The effect of strain on viscoelastic properties of O/W emulsions for LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water), (B) emulsion 3 (6% protein, 36.26% oil, 57.74% water) and (C) emulsion 5 (6% protein, 34% oil, 60% water)

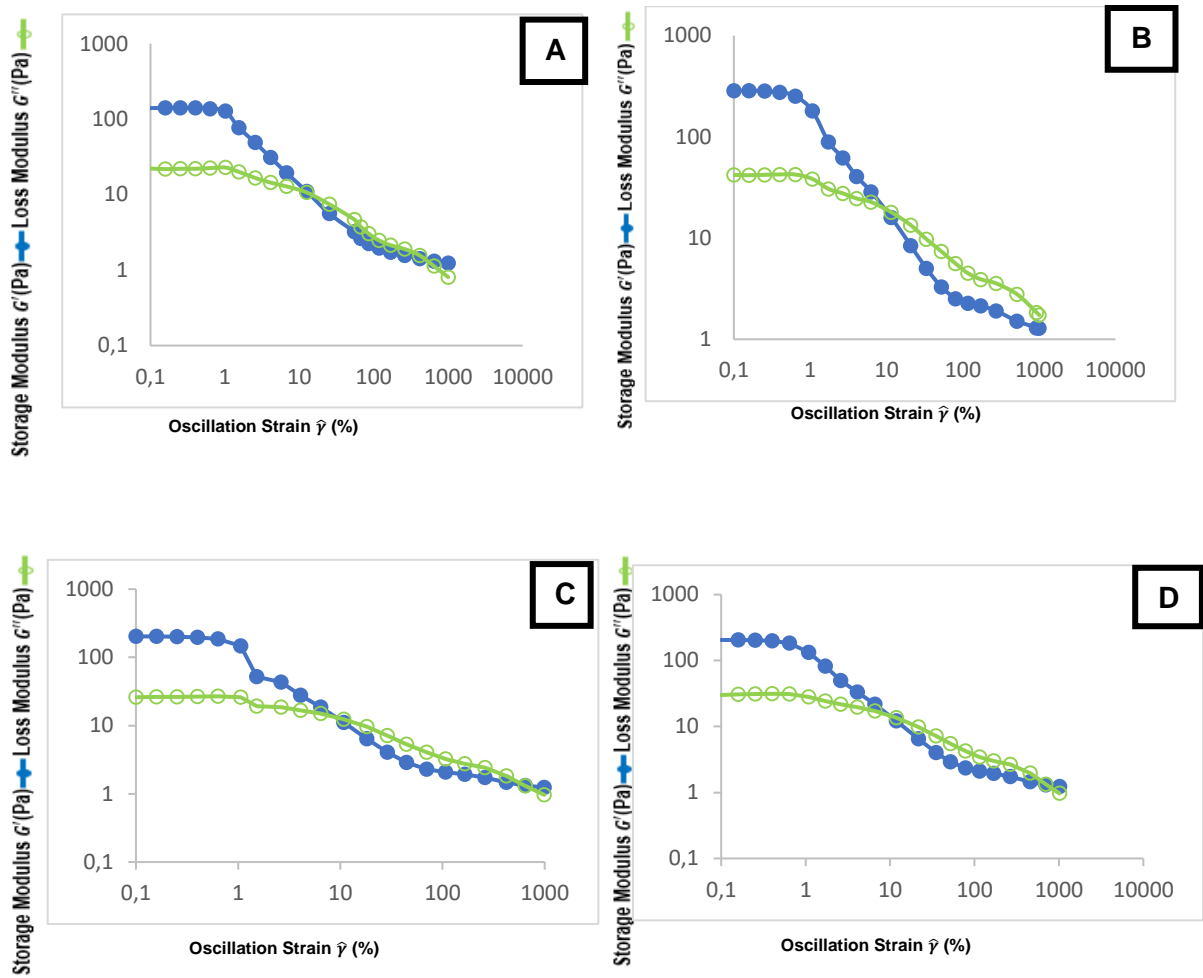


Figure 4.19 The effect of strain on viscoelastic properties of O/W emulsions for MPEs: (A) emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), (B) emulsion 7 (10.50% protein, 34.50% oil, 55% water), (C) emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and (D) emulsion 9 (10% protein, 30% oil, 60% water)

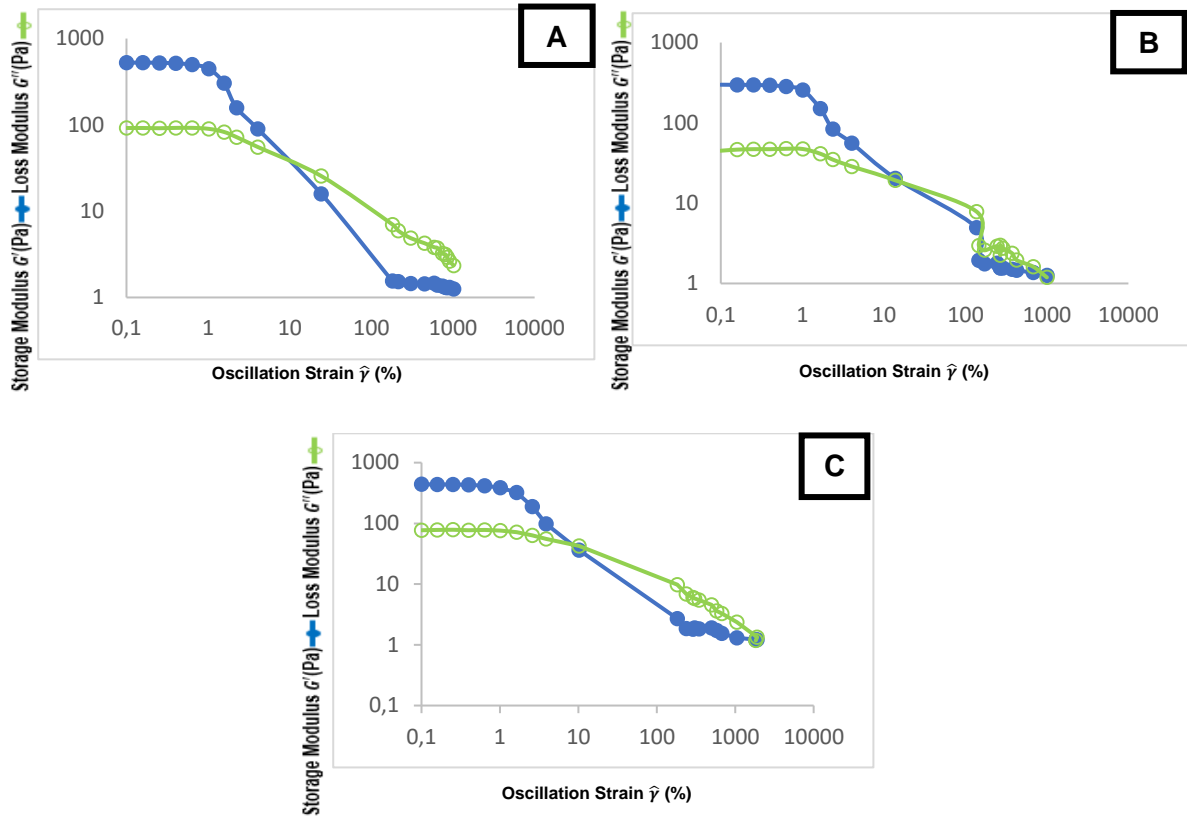


Figure 4.20 The effect of strain on viscoelastic properties of O/W emulsions for HPEs: (A) emulsion 4 (15% protein, 30% oil, 55% water), (B) emulsion 6 (12.53% protein, 30% oil, 57.47% water), and (C) emulsion 10 (12.78% protein, 32.22% oil, 55% water)

All emulsions comprised of the elastic and the viscous portion because there was no case where either G' or G'' was zero. From appendix C, Table C1 to Table C10, all samples had a phase angle that lied between 0 and 90° which characterises them as viscoelastic according to Wyss et al. (2007). Therefore, all emulsions regardless of composition had viscoelastic properties. Though the samples were tested over the same strain range, the composition of protein, oil and water of the emulsions had an effect on the moduli.

The amount of protein had an effect on the thickness of the emulsions. An emulsion with more protein would have more oil and water molecules held together therefore having greater thickness. Due to this, the HPEs had a higher moduli followed by the MPEs then the LPEs before the point where $G' = G''$. Since there is less protein holding oil and water molecules together in LPEs, when energy is applied, bonds are easily broken compared to a system which contains more protein that is holding oil and water molecules hence the elasticity of the LPEs was seen to be lower compared to the HPEs.

The viscous portion (loss modulus) of the emulsions indicates how much energy was released from the system. This energy also considered as heat energy could be generated in different ways. The molecules which are already in contact with the walls of the cylinder may create friction resulting in heat energy. Collisions amongst molecules may result in additional heat energy. Emulsions with high protein had a higher G'' than emulsions with low protein.

Viscosity corresponds to the friction amongst molecules (Painter and Coleman, 2009), which implies that a solid material would have more friction amongst its molecules as they are closely packed than a liquid. As friction arises between molecules, heat energy may be dissipated. Therefore, the HPEs had higher heat energy dissipated as they were thicker than the MPEs followed by the LPEs due to higher internal friction of molecules. Though all emulsions may release heat energy due to friction between the molecules and the surfaces of the cylinder, the HPEs had a higher loss modulus followed by the MPEs then the LPEs. Consequently, the heat energy as a result of friction amongst molecules decreased in that order relating to how the molecules were closely packed.

Both the storage and loss moduli values for HPEs were higher, followed by those of MPEs and last those for LPEs. This trend was observed before the crossing of G' and G'' . These results are in agreement with the work of Bengoechea et al. (2009) and Primožic et al. (2017). Bengoechea et al. (2009) performed oscillatory tests on O/W emulsions stabilised by egg protein and reported that the emulsions had viscoelastic properties with the elastic portion being dominant. Bengoechea et al. (2009) reported that emulsions with a protein concentration of 2, 4 and 5%, both G' and G'' increased as the concentration increased where trend was observed before the crossing of G' and G'' . Primožic et al. (2017) performed a strain amplitude sweep test on O/W nanoemulsions stabilised by lentil protein isolate with a varying protein concentration of 1, 1.5, 2, 3 and 5%. They reported that the nanoemulsions demonstrated viscoelastic behaviour with the elastic portion being dominant before the crossing of G' and G'' . They also reported that as the concentration increased, both G' and G'' increased.

The LPEs illustrated that the composition of an emulsion does affect its moduli. These emulsions had the same amount of protein with varying oil and water compositions, which caused a difference in their moduli. Having more water would cause an emulsion to be less viscous thus would decrease the elasticity. Emulsion 1 (6 % protein, 39 % oil, 55 % water), emulsion 3 (6 % protein, 36.26 % oil, 57.74 % water) and emulsion 5 (6 % protein, 34 % oil, 60 % water) demonstrated that as the water was increased, the average G' decreased indicating that as the viscosity of emulsions decreased the elasticity decreased. The average G' at a strain of 0.1% for emulsion 1, 3 and 5 was 110.31, 69.31 and 13.04 Pa respectively. If there are more oil droplets in an emulsion but insufficient protein adsorbed on them, the droplets are likely to join and thus increase the loss modulus. This is also seen in the LPEs,

where the protein content is the same, but the oil content is different. The following indicates how the increase in oil content affected the average G'' at a strain of 0.1%: emulsion 1 (13.60 Pa), emulsion 3 (9.82 Pa) and emulsion 5 (6.78 Pa).

Table 4.12 provides information about the LVR, which demonstrates at which strain range the structure of emulsions were not disturbed, implying stability. Table 4.12 also provides information on the strains at which phase transitions of the O/W emulsions occurred from being viscoelastic to being liquid-like.

All emulsions had a LVR illustrating to have been stable at low strains, however, as the strain increased, both G' and G'' deviated and decreased. As low strains do not disturb the structure of the emulsions while higher strains affect their structure, this implies that products of similar composition should for example be packaged during transportation such that minimal application of greater force is prevented in order not to disturb them. The LVR of the MPEs ended at a strain of 0.64% except for emulsion 2. Emulsion 4, 6 and 10 had their LVR ending at strains of 1.02, 1.02 and 1.01%, respectively. The HPEs had the longest LVR amongst all emulsions. This finding confirms that the HPEs are more stable compared to the MPEs and LPEs hence the larger LVR.

Table 4.12 LVR and Cross-Over Point of O/W Emulsions

Emulsion Category	Emulsion	Protein %	Oil %	Water %	End point of LVR (Strain %)	Cross- over point (strain %)
LPEs	1	6.00	39.00	55.00	0.40	98.64
	3	6.00	36.26	57.74	0.14	-
	5	6.00	34.00	60.00	0.64	-
MPEs	2	9.25	33.25	57.50	1.01	12.50
	7	10.50	34.50	55.00	0.64	10.00
	8	8.14	36.63	55.23	0.64	9.00
	9	10.00	30.00	60.00	0.64	11.00
HPEs	4	15.00	30.00	55.00	1.02	10.00
	6	12.53	30.00	57.47	1.02	14.00
	10	12.78	32.22	55.00	1.01	9.00

The HPEs were expected to have higher LVR's followed by the MPEs then the LPEs. This was not entirely the case, as some of the emulsions did not support this phenomenon. For example, it was not expected for emulsions 2 to have its LVR ending at 1.01%, which was in the range of the HPEs. Perhaps their molecules had less kinetic energy making them more rigid and were able to overcome higher strains compared to the other MPEs. It was also not expected to have a LPE with a long LVR. However, emulsion 5 had a LVR that ended at strains of 0.64%, which was in the range for the MPEs. This may have occurred due to wall slip. When there is wall slip, the shearing geometry does not stick to the emulsion (Meeker et al., 2004) hence the structure of emulsion 5 was not affected until higher strains than expected.

Some emulsions had a crossing point of G' and G'' and some did not. It is at this point where G' and G'' are equal. All the MPEs and HPEs demonstrated the crossing of G' and G'' . It was expected that the HPEs would have a crossing of G' and G'' at higher strains followed by the MPEs then the LPEs. The crossing of G' and G'' of the MPEs and HPEs shows the transition from being gels to liquid-like. Though the LPEs appeared to be liquid-like, since they contained both protein and oil, they were not completely viscous hence they were viscoelastic. Therefore, their crossing of G' and G'' also showed a transition from being viscoelastic to being fluid-like. However, there was no clear trend of the point of crossing of G' and G'' amongst all emulsions probably due to inconsistency in protein desorption.

Emulsion 3 and 5 had no crossing demonstrating that there was no transition of phase. Emulsions 1 and had a crossing of G' and G'' at a strain of 98.64 %, which was higher than some of the HPEs and MPEs. This also implies that it transitioned from being viscoelastic to becoming fluid-like. For 1 emulsions to have a crossing of G' and G'' at higher strains than anticipated and emulsion 3 and 5 not to have a crossing of G' and G'' could have the same

reason as described previously of wall slip. Since these emulsions had more oil droplets not covered by protein, that could have encouraged wall slip.

The crossing point of G' and G'' of the MPEs ranged from strains of 9 to 12.50% with emulsion 2 having a crossing at the highest strain and emulsion 8 with the least. Emulsion 6, which is one of the HPEs, had a crossing at a strain of 14.00% which was higher than all emulsions except for emulsion 1 due to the same reason of wall slip as discussed in the previous paragraph. Emulsions 4 and 10 (HPEs) had a crossing at strains of 10.00 and 9.00%, respectively which was in the range for the MPEs.

Though the protein content made the HPEs thicker than the LPEs, they were not able to overcome higher strains; hence, they transitioned at lower strains. According to Ungar (2010) for stiff food products, increased stress should be applied to induce sufficient strain that can allow irreversible deformation. Therefore, as the HPEs had a high moduli during the LVR, it was expected that the crossing of G' and G'' would occur at more significant strains as a result of higher stress being required for thicker emulsions to deform. As oil droplets may become entrapped in entangled protein networks, (de Figueiredo Furtado et al., 2018) it could be that some of the protein chains in these HPEs were not adequately entangled as entangled chains have more strength (Kolasinski, 2017). Therefore, it did not require higher strains for G' and G'' to cross for these emulsions as their strength could have been affected by insufficient entangling of some protein chains. Perhaps the friction between the emulsion and walls could have produced energy that untangled the protein and making it easier to break bonds hence the transition of the phase occurred at lower strains.

The findings of some of the O/W emulsions are in agreement with Bower et al. (1999) who conducted an amplitude strain sweep test on commercial mayonnaise and protein stabilised emulsions and illustrated that the crossing of G' and G'' occurred at strains between 10 and 20%. The MPEs (emulsions 2, 7 and 9) and HPEs (emulsions 4 and 6) had a crossing of G' and G'' at strains between 10 and 20%.

4.6.2 Effect of frequency on the viscoelastic properties of O/W emulsions

The purpose of performing the frequency test was to describe the behaviour of O/W emulsions during long term storage and the effect of slow and high movements on the viscoelastic characteristics of O/W emulsions. The increase in frequency increased both the storage and loss modulus. No crossing of the G' and G'' curves occurred for all emulsions. Figures 4.21 to 4.23 show the effect of frequency on O/W emulsions stabilised with BBN protein isolate.

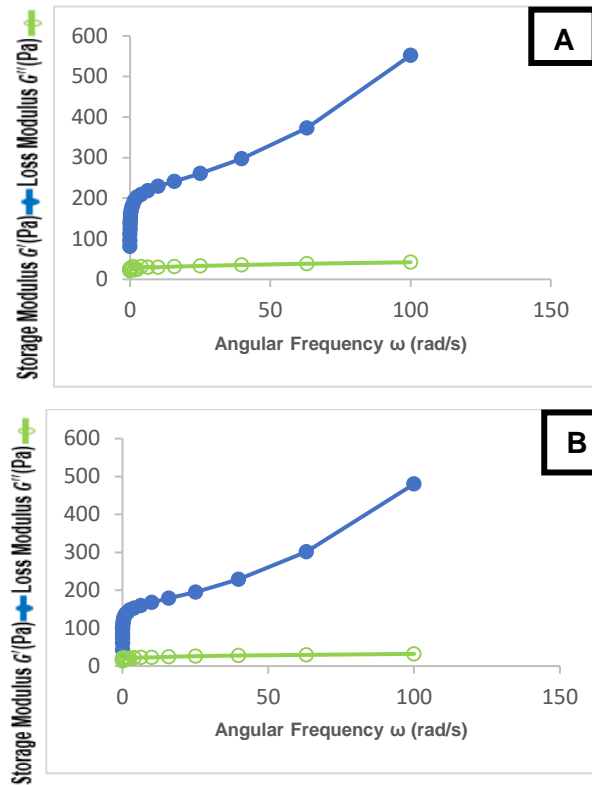


Figure 4.21 Effect of frequency on the moduli of LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water) and (B) emulsion 5 (6% protein, 34% oil, 60% water)

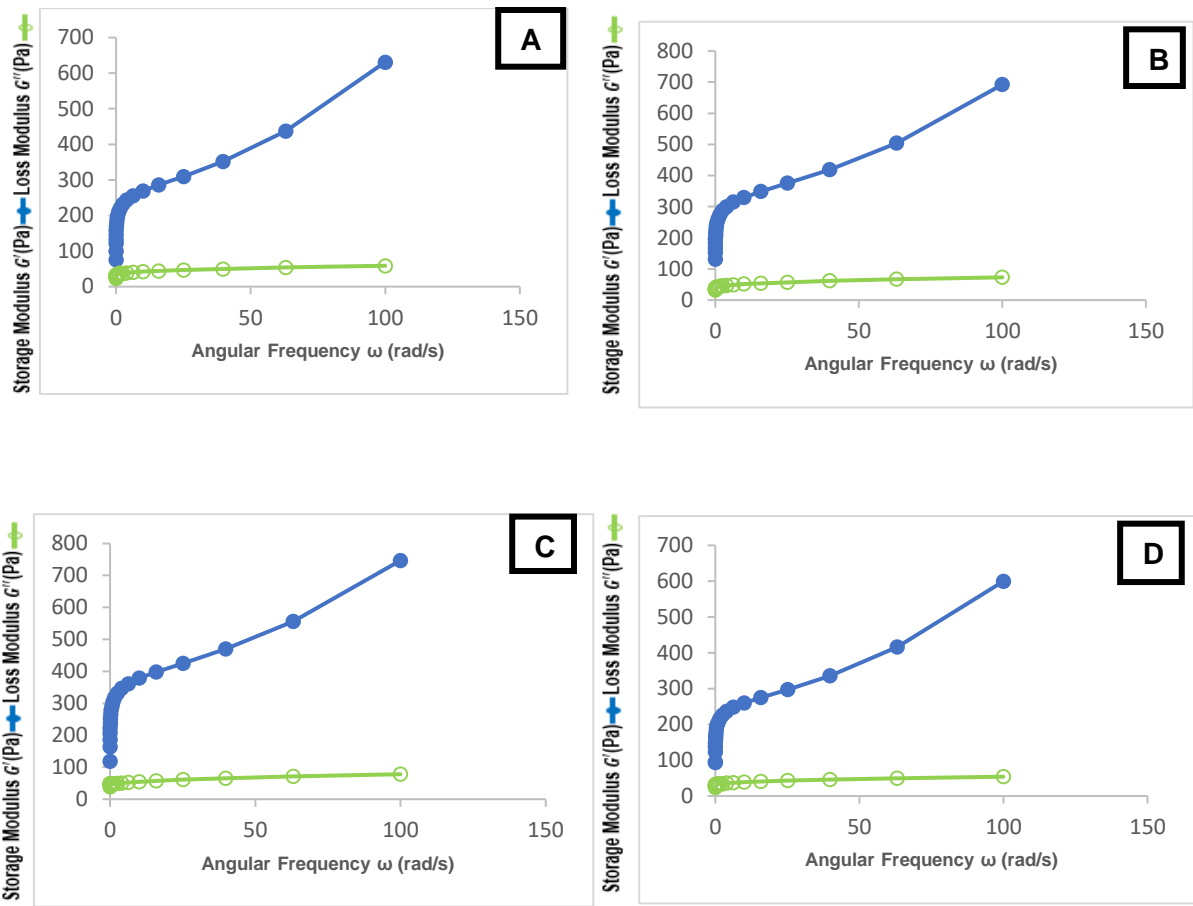


Figure 4.22 Effect of frequency on the moduli of MPEs (A) emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), (B) emulsion 7 (10.50% protein, 34.50% oil, 55% water), (C) emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and (D) emulsion 9 (10% protein, 30% oil, 60% water)

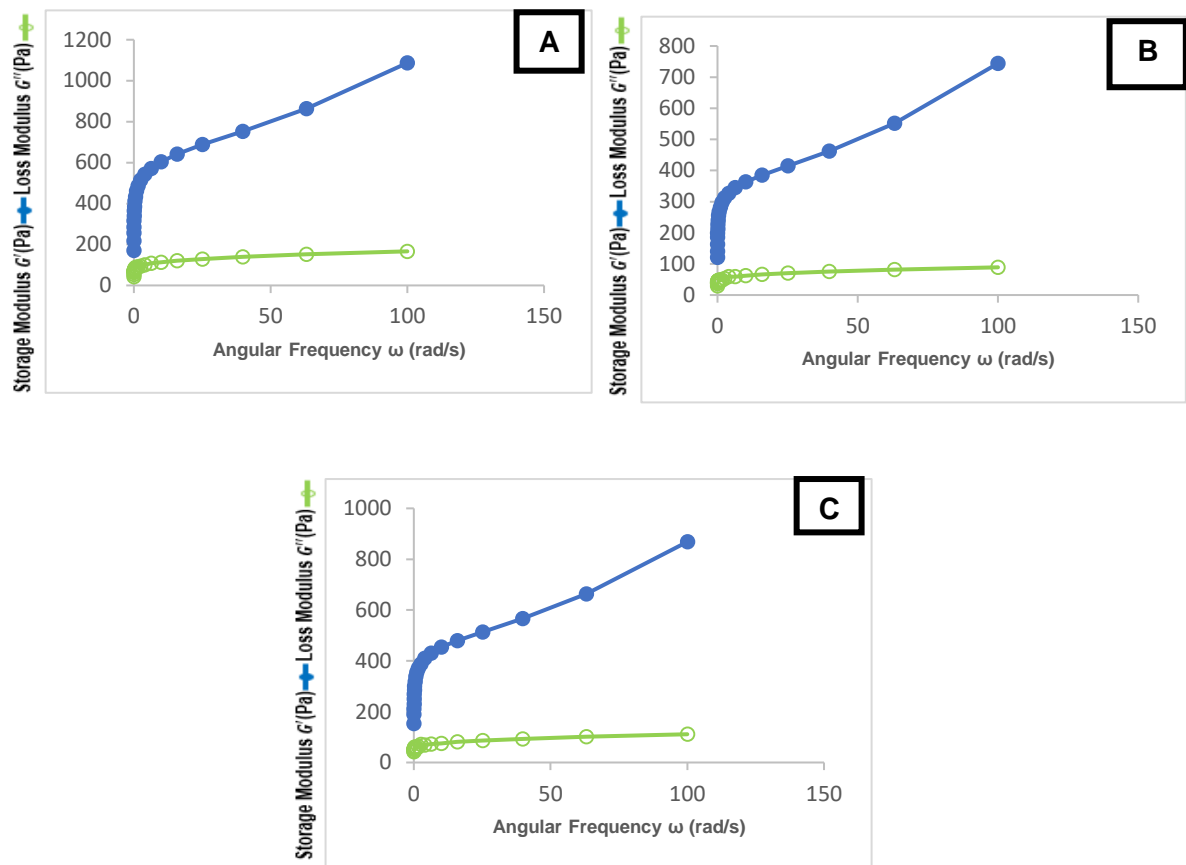


Figure 4.23 Effect of frequency on the moduli of HPEs: (A) emulsion 4 (15% protein, 30% oil, 55% water), (B) emulsion 6 (12.53% protein, 30% oil, 57.47% water) and (C) emulsion 10 (12.78% protein, 32.22% oil, 55% water)

To perform the oscillatory frequency sweep test, a strain of 0.2% was chosen from the amplitude test as all emulsions were still at their LVR at this strain except for emulsion 3 where it's LVR ended at a strain lower than 0.2%. For some of the MPEs and HPEs, the LVR occurred even at higher strains; however, 0.2% was chosen to be consistent for all the emulsions. Peng et al. (2018) performed a frequency sweep test on whipped cream at a range of 1 to 100 Hz at 0.5% strain and demonstrated that both the storage and loss modulus increased with increasing frequency. This study demonstrated the same trend observed by Peng et al. (2018). At low frequencies, all samples had a low modulus and at high frequencies, the moduli were greater. This behaviour explains the increase of the elastic and viscous properties of the emulsion with increase in frequency. At a high frequency (as stress is applied for a short period), the molecules retain the energy and does not have enough time to use that energy to initiate deformation. However, upon removing the stress, it uses this energy to return to the original state hence the relaxation time is short. According to De Vicente (2012), at high frequencies, there is not enough time to enable polymer chains to rearrange or disentangle while they have enough time to disentangle at low frequencies. According to Mezger (2006), at high frequencies, polymer entanglements are less mobile while at low frequencies, they are

more mobile. Consequently, at a high frequency, there is insufficient time to get the molecules at an excited state which initiates mobility of molecules to allow the rearrangement and disentanglement of polymeric chains and making it easy for deformation to occur. Therefore, the higher the frequency, the quicker the molecules relax and return to the original and having lesser time to provide energy to allow the movement of molecules thus creating a more elastic sample with no disturbance in its structure. At a low frequency, molecules have sufficient time to reach the excited state, become mobile and start to disentangle and making it easy for deformation to occur. By the time the stress is removed, there is insufficient stored energy to cause the molecules to completely return to its original state. Therefore, the lower the frequency, the more mobile the molecules become leading to a more viscous behaviour.

For this study, at a low frequency, the elastic portion was dominant as the G' was always higher than the G'' indicating that the samples were stable. The frequency test took approximately 3 hours and 40 minutes to complete. It was explained that the LPEs were stable for 2 hours from visual observation. However, the increase in the elasticity of the LPEs as the frequency increased suggests that the destabilisation rate of these emulsions could have been lowered. Though both the storage and loss modulus increased, the storage modulus did not increase linearly and the increase of the loss modulus was very gradual. It is so gradual that one would perceive its entirely horizontal and no clear increase occurred. However, looking at the values of storage modulus at appendix D, the loss modulus is low at low frequencies and higher at high frequencies. Therefore, there was an increase in the loss modulus. However, for most of the emulsions, in between, the loss modulus was fluctuating. This could have been caused by inconsistency in friction and the release of energy as collisions occur randomly.

The storage modulus had a steep increase at the beginning for all emulsions. This is due to the combination of the increase in frequency and the energy that the molecules still possessed immediately after homogenisation to form collisions leading to bond formation. This section is followed by a gradual increase (starting from 10 rad/s). The gradual increase suggests that the molecules did not have as much energy as they had initially and the elasticity only increased due to only the increase in frequency and this is supported by Mezger (2006), who stated that as frequency increases, the rigidity of a polymer also increases. Though there was an increase in G'' as the frequency increased, it was not affected significantly. This implies that throughout the frequency range, the emulsions were moving towards being solid-like as the elastic portion increased throughout the frequency range. The viscous behaviour was higher for HPEs as more molecules could have caused more friction as compared to that of the LPEs.

Bengochea et al. (2006) performed an oscillatory frequency test on O/W emulsions stabilised by soy protein isolates at a frequency between 0.01 to 100 rad/s. The G' had an increasing trend throughout the frequency range and G'' showed an increasing trend only from 10 rad/s. As the protein concentration was increased from 1 to 3%, both the moduli increased over the

frequency range. Puppo et al. (2003) also performed an oscillatory frequency test on O/W emulsions stabilised by soy protein isolates and showed that there was an increase in elasticity as the frequency increased. Secondly, the study showed that the increase in protein concentration over the frequency range increase the G' values. This study demonstrates that the HPEs had higher moduli than the LPEs, which had the lowest moduli over the same frequency. The MPEs had higher moduli than the LPEs. Emulsion 8 (MPE) had a higher storage modulus than emulsion 6 (a HPE) where emulsion 8 had an average storage modulus of 746.93 Pa at 100 rads/s and emulsion 6 with 744, 15 Pa at 100 rads/s. However, the difference is not significant. Besides, the MPEs had a lower modulus than the HPE over the same frequency range. The reason for a higher elasticity for emulsions with high protein could be that more protein chains provided for rigidity than those with fewer protein.

According to Ikeda and Nishinari (2001), weak gels are characterised by $\tan\delta > 0.1$. Therefore, all emulsions in this study are weak gels as their $\tan\delta \left(\frac{G''}{G'}\right)$ was greater than 0.1.

4.6.3 Effect of temperature on the viscoelastic properties of O/W emulsions

Figures 4.24 to 4.26 shows the effect of temperature on viscoelastic properties of O/W emulsions, which was performed to analyse the storage temperature of O/W emulsions from refrigeration temperature, room temperature and at higher temperatures up until 40°C. There was a difference in the viscoelastic characteristics of O/W emulsions at refrigeration and room temperatures and this is further described in this section. This section also describes the reason the emulsion stability can be enhanced by storing at refrigeration temperature. There was no crossing of G' and G'' curves in any of the emulsions suggesting that the temperature range did not change the phase of the O/W emulsions. Throughout the temperature range the moduli of the HPEs was high, followed by the MPEs, then the LPEs.

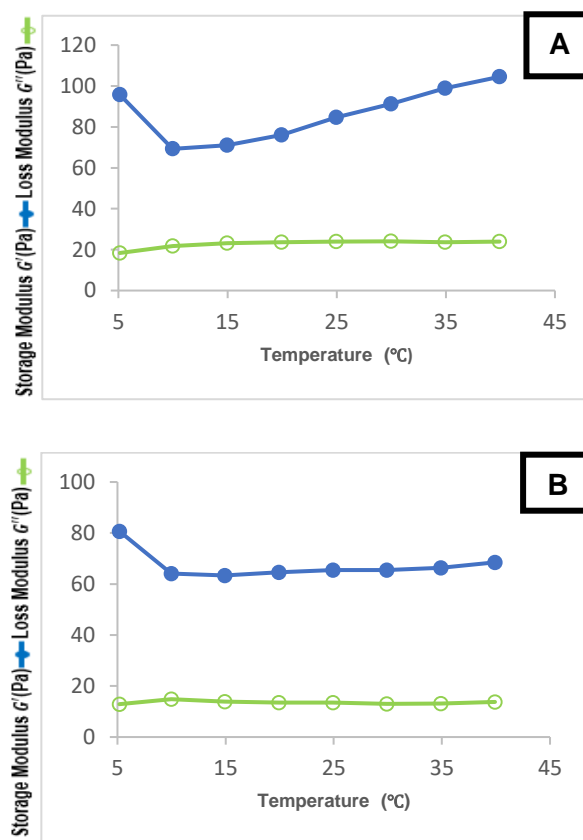


Figure 4.24 Effect of temperature on the moduli of LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water) and (B) emulsion 5 (6% protein, 34% oil, 60% water)

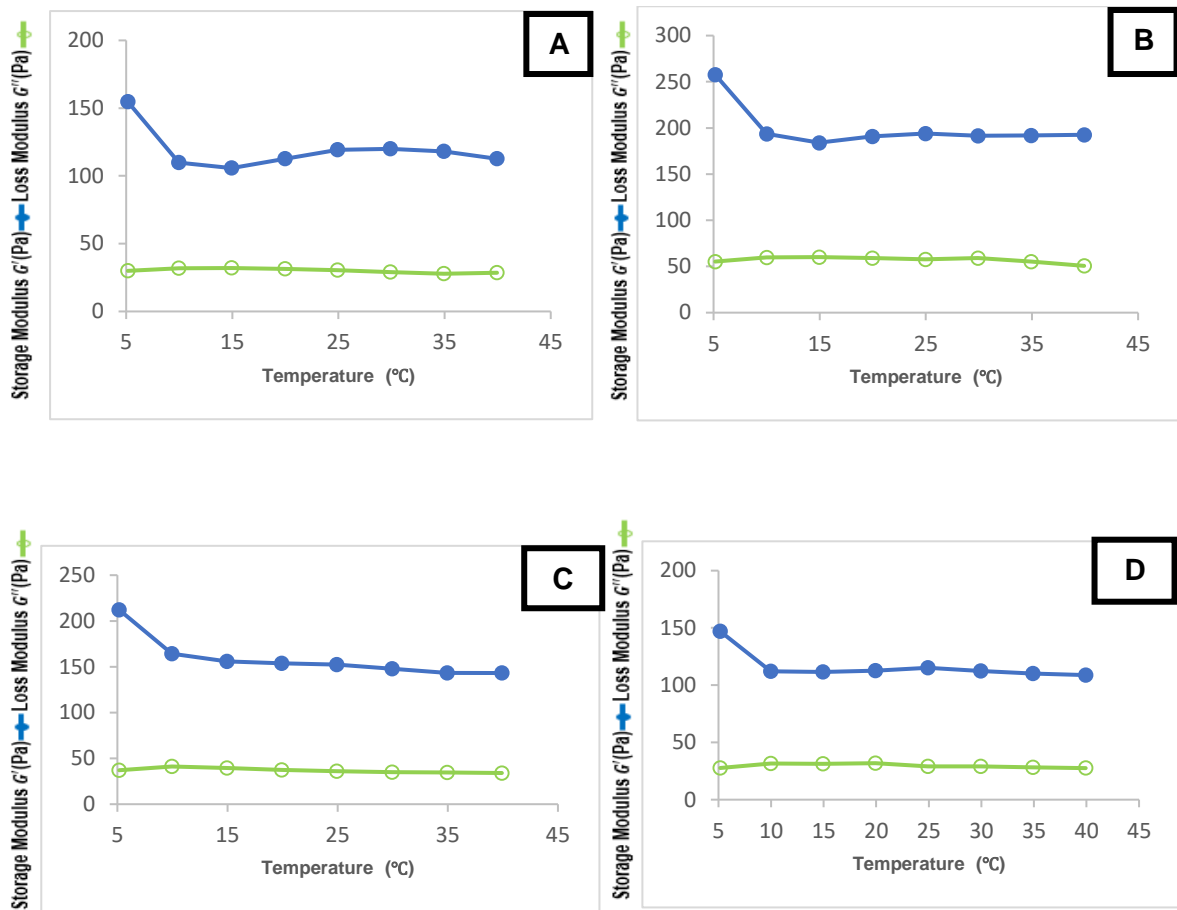


Figure 4.25 Effect of temperature on the moduli of MPEs: (A) emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), (B) emulsion 7 (10.50% protein, 34.50% oil, 55% water), (C) emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and (D) emulsion 9 (10% protein, 30% oil, 60% water)

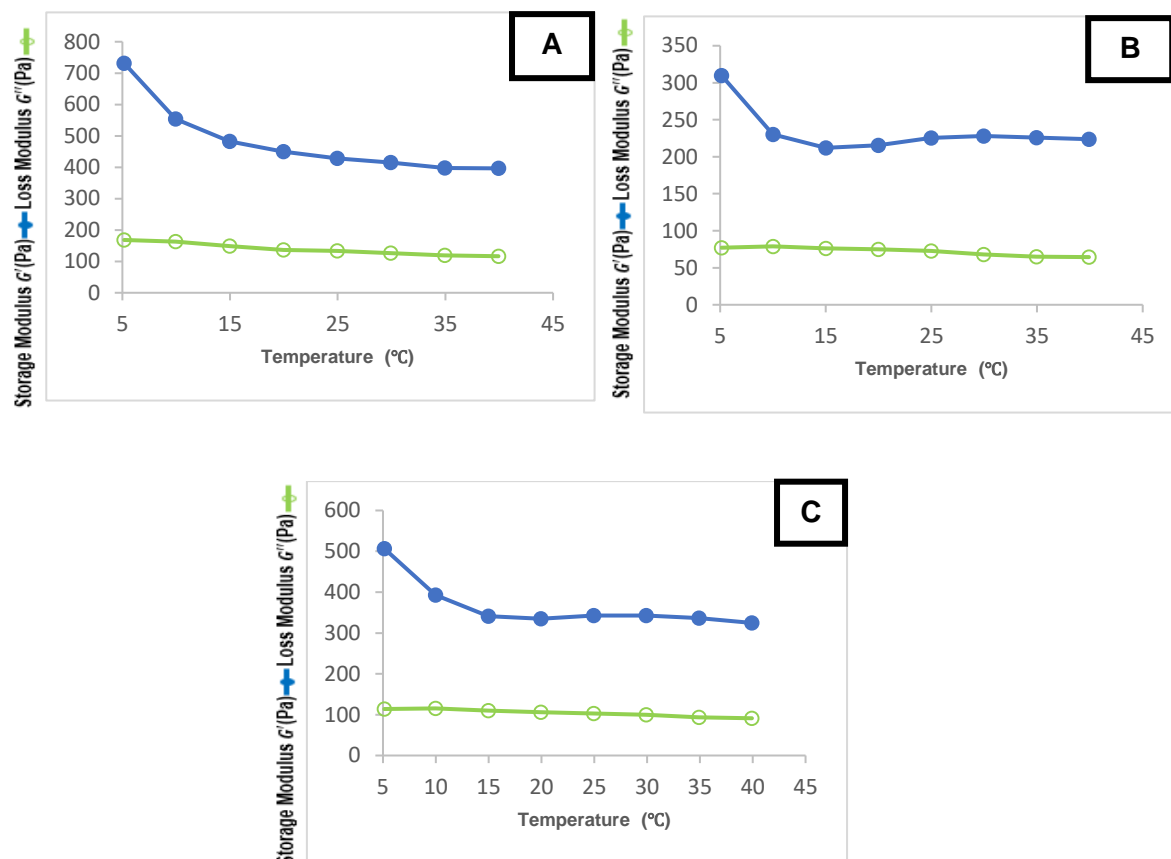


Figure 4.26 Effect of temperature on the moduli of HPEs: (A) emulsion 4 (15% protein, 30% oil, 55% water), (B) emulsion 6 (12.53% protein, 30% oil, 57.47% water) and (C) emulsion 10 (12.78% protein, 32.22% oil, 55% water)

Between 10 to 40°C, there was no detrimental effect on the structure of the samples as no crossover occurred between the G' and G'' curves. Between these temperatures, the G' and G'' curves were horizontal and almost parallel except for emulsions 1 and 3 as shown in Figures 4.24 A and 4.24 B respectively. These emulsions had an increase in G' between these temperatures. Since there is ease of movement in the liquid-like emulsions, probably the increase in temperature enhanced the mobility of molecules leading to collisions that may have resulted in bond formation hence the increase in the elasticity.

Between the temperatures 10 to 35°C, which resembles cold to room temperature, there was no negative effect on the structure of the emulsions thus demonstrating stability of emulsions under such conditions.

The higher temperatures (35 to 40°C) resembled temperatures above room temperatures. Stability was maintained between these temperatures as the elastic portion remained dominant over the viscous portion. The increase in the viscous portion would have been caused by the heat energy provided by the increase in temperature leading to permanent deformation. The energy could have caused more mobility in molecules and creating disentanglements of chains and leading to bonds breaking and thus increasing the loss modulus. This was not observed

which suggest that the intermolecular forces were able to withstand the heat energy generated from the higher temperatures resulting in no bonds breaking. Therefore, at this temperature range, the HPEs and MPEs did not liquify and the LPEs did not destabilise as their G'' did not increase.

As the temperature increased from 5 to 10°C which normally represents refrigeration to cold temperatures, there was a significant decrease in G' illustrating a decrease in the elasticity of the samples. Since crystals form when a fluid experiences low temperatures (Godoi et al., 2019), the steep decrease in G' may suggest that the increase of temperature from 5 to 10°C may have caused crystalline structural breakdown. Between these temperatures, the decrease in elasticity may indicate that the molecules were agitated. However, as the temperature increased further from 10°C, the structure of the emulsions appears to have stabilised as there was no further decrease in the elasticity.

At refrigeration temperature, the elasticity is higher than that at room temperature, meaning that at refrigeration temperature, destabilisation would take longer to occur. Therefore, refrigerating O/W emulsions can enhance the stability. A study conducted by Sapei et al. (2017) concluded that destabilisation rate constants of O/W emulsions stored at refrigeration temperature were two times lower than those of emulsions stored at room temperatures. Hence, storing at refrigeration temperature prolongs destabilisation compared to storing at room temperature. Therefore, the findings of Sapei et al. (2017) supports the conclusion made in this study that refrigerating O/W emulsions can enhance the stability.

4.6.4 Effect of time on the viscoelastic properties O/W emulsions

The time sweep test was conducted to analyse if there were any changes in the viscoelastic properties of the O/W emulsions in one hour. Changes occurred as there was an increasing trend of G' and a gradual increase in G'' . The emulsions were stable during the first hour as there was no decline in the storage modulus and no steep increase of the loss modulus. To further confirm the stability and no phase change of the O/W emulsions occurring during the first hour, no crossing of the G' and G'' curves took place. Figures 4.27 to 4.29 illustrate the viscoelastic behaviour of O/W emulsions during the first hour after homogenisation.

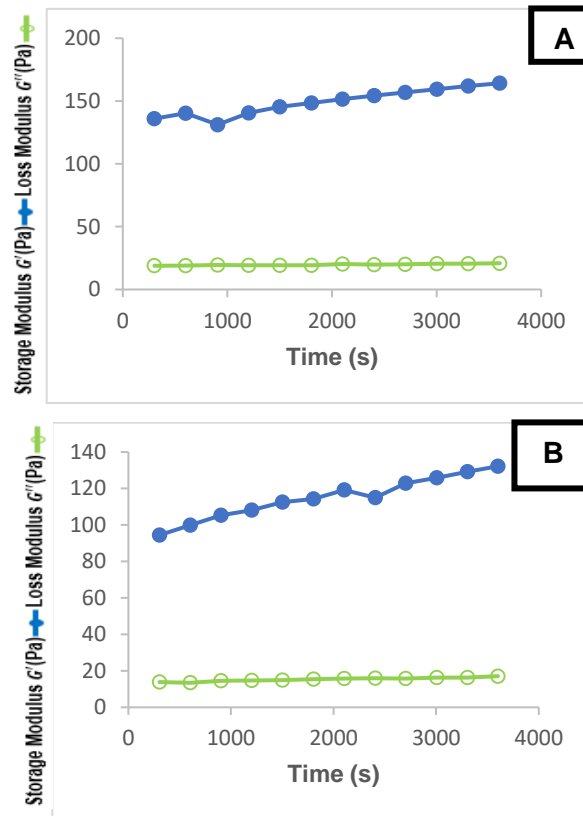


Figure 4.27 Effect of time on the moduli of LPEs: (A) emulsion 1 (6% protein, 39% oil, 55% water) and (B) emulsion 5 (6% protein, 34% oil, 60% water)

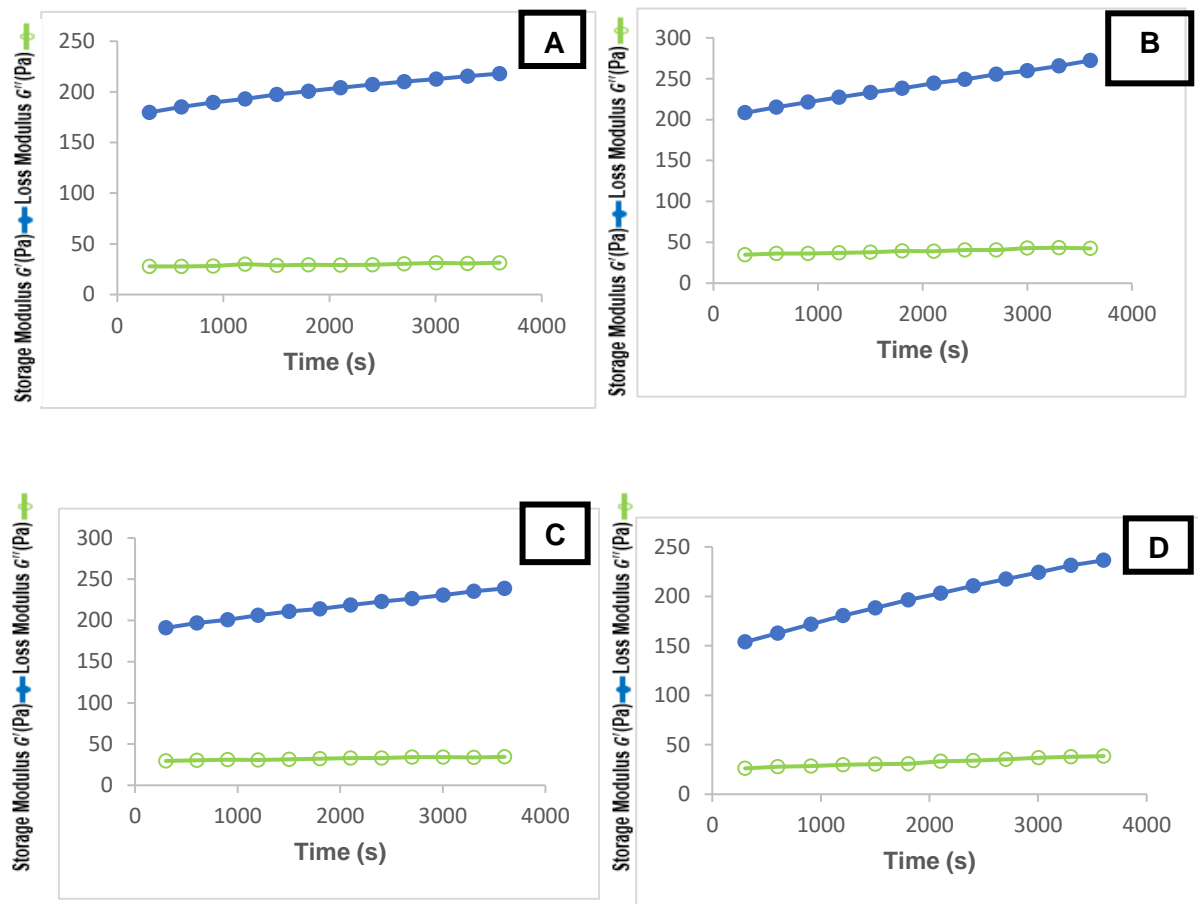


Figure 4.28 Effect of time on the moduli of MPEs: (A) emulsion 2 (9.25% protein, 33.25% oil, 57.50% water), (B) emulsion 7 (10.50% protein, 34.50% oil, 55% water), (C) emulsion 8 (8.14% protein, 36.63% oil 55.23% water) and (D) emulsion 9 (10% protein, 30% oil, 60% water)

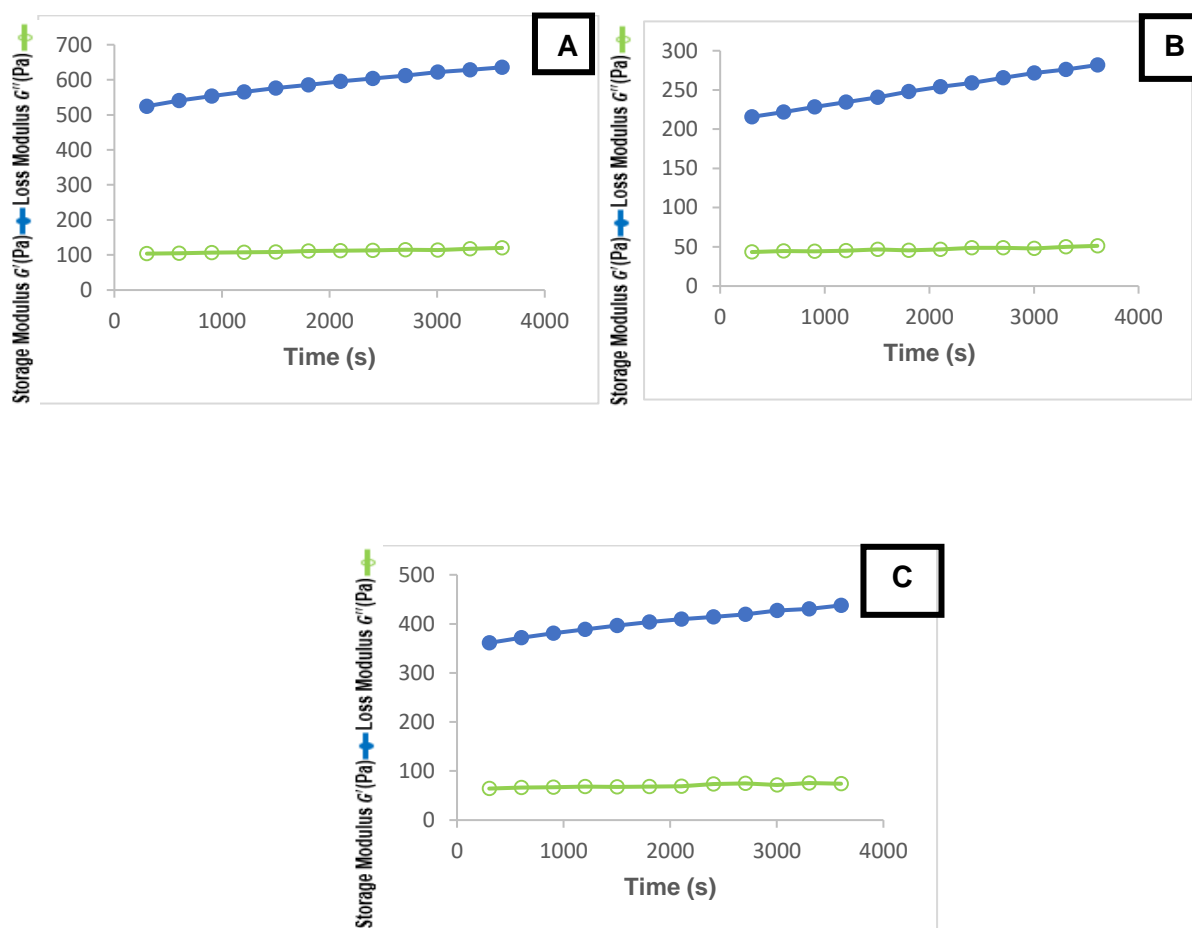


Figure 4.29 Effect of time on the moduli of HPEs: (A) emulsion 4 (15% protein, 30% oil, 55% water), (B) emulsion 6 (12.53% protein, 30% oil, 57.47% water) and (C) emulsion 10 (12.78% protein, 32.22% oil, 55% water)

Time affected the viscoelastic properties of O/W emulsions through structural changes. The trend of the G' and G'' curves suggest that changes occurred within the first hour after homogenisation. If no structural changes occurred then the G' and G'' curves would have been constant and horizontal throughout the time range. The structural changes for all samples did not indicate instability; instead, the dominance of the elastic portion demonstrated that there was the strengthening of bonds during the first hour after homogenisation. All samples indicated an increase of both the G' and G'' demonstrating an increase in the elastic and viscous portion respectively. After homogenisation molecules may still possess energy which enabled collisions leading to bond formation. Secondly polymer cross-linking could have occurred hence elasticity increased during one hour after homogenisation.

As homogenisation took place, the samples were warm. It is this heat that causes bonds to be stretched. However, as the samples continue to cool down, the molecules came close together, increasing and strengthening bonds and making samples to be thicker and thus contributing to the increase of the elastic portion. The increasing trend of the G'' remained beneath the G' curve and did not cross over to become dominant over the elastic portion thus illustrating that

transition of phases did not occur during the first hour. All emulsions demonstrated a very gradual increase in G'' , with fluctuations in between (Appendix F). The increase was not significant such that the graphs appear to be constant. The increase in the viscous portion can be explained by the continuous movement of molecules after homogenisation which created collisions which did not result in bond formation, therefore due to intense friction between the molecules, heat energy could have been generated. Additional friction leading to heat energy would be due to molecules moving against the surface of the walls thus increasing the loss modulus.

4.7 Chapter Summary

The LPEs were not stable as phase separation was observed. This correlated to the rheology results, which demonstrated that these emulsions were the least viscous at minimum shear rate and having the least modulus in the LVR. The LPEs had a variation of particle sizes leading to particle growth. These emulsions took the shortest amount of time to start separating (instability). The HPEs had no phase separation for a longer period of time because the emulsions were thick, with higher viscosity at minimum shear rate and a higher moduli in the LVR. They had more uniform and dispersed droplets, which did not encourage particle growth compared to the LPEs. The stability of these emulsions was also confirmed by visual observation that no phase separation occurred for 3 weeks. The optimum emulsion with 15% protein, 30% oil and 55% water had a high viscosity at lower shear rates and high moduli in the LVR, uniform droplets with no occurrence of particle growth and a longer LVR compared to the majority of the emulsions. The temperature from 5 to 40°C did not negatively affect its stability.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

Protein was extracted from the brown coloured BGNF and the yield was 16.6%. Therefore, the objective of extracting protein from BBGN was achieved. The protein was high in glutamic acid and also comprised of several essential amino acids. BBGN protein can be used not only to replace protein from an animal source in food products but can also provide flavour as it comprise of the majority of amino acids which provide flavour. This illustrates that the objective of characterising the amino acid profile of the extracted protein was fulfilled.

The objective of determining the stability characteristics of O/W emulsions stabilised with BBGN protein was achieved as the variation in emulsion appearance over time, backscattering intensity and emulsion images were determined for the LPEs, MPES and the HPEs. BBGN protein has shown to have emulsifying properties as all the HPEs were stable for four weeks except the emulsion with 12.78% protein concentration which was stable for three weeks. The MPEs were stable for 12 hours and the LPEs for 2 hours. The turbiscan showed instability of the LPEs by having a variation in backscattering between 5 and 15 mm from the bottom of the tube which demonstrated phase separation. Coalescence was also present in the LPEs which was demonstrated by a thick horizontal line in the turbiscan profiles. For stable emulsions, minimal or no variation in backscattering intensity occurred which was demonstrated in most of the HPEs.

The composition of emulsions affected the viscosity. The LPEs had a lower viscosity than the HPEs. Though the viscosity was different for all emulsions, they all exhibited shear thinning throughout the shear rate range. All emulsions exhibited viscoelastic properties and also demonstrated weak gel properties. The storage and loss modulus was higher for the HPEs followed by the MPEs then the LPEs during their LVR. The frequency affected all emulsions as both the storage and loss modulus increased with the increase in frequency. The temperature from 10 to 40°C did not affect the structure as the G' and G'' curves were horizontal and parallel except for some of the LPEs. However, at refrigeration temperature, the emulsions had high G' values illustrating greater stability at lower temperatures. During the first hour after homogenisation, the samples still possessed energy from the mixing process as shown by the increase in the storage modulus indicating bond formation. Information provided about the viscosity and viscoelastic properties of the LPEs, MPEs and the HPEs illustrates that the objective of determining the flow and viscoelastic properties of O/W emulsions stabilised with BBGN protein was achieved.

The correlation drawn from the techniques used to analyse the O/W emulsions was that the LPEs were liquid-like (by visual observation), unstable (showed by the turbiscan profiles), had

the least viscosity and modulus (shown by the rheological data) and had non-uniform particle sizes (shown by the light microscope) than the HPEs.

The BBGN protein demonstrated its ability to emulsify emulsions. This occurred as there were no additional materials. Since different materials possess different stability and rheological properties, the addition of additives in the O/W emulsions would have an effect on the emulsions. It is therefore recommended that for further research, the stability and rheological properties of O/W emulsions be tested when stabilised by a combination of BGN protein and additives. It is recommended to study the interaction of BGN protein with other emulsifiers (for example from different legumes) in O/W emulsions. Different O/W emulsions in the food industry are formulated using different mixing equipment at different speeds. Therefore, it is recommended that for further research, different equipment at different speeds be used for comparison of the stability and rheological properties of the emulsions.

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APPENDIX

Appendix A: Protein Extraction Data

Table A1 Protein Extraction Data

Run	Protein Extracted (g)	Run	Protein Extracted (g)	Run	Protein Extracted (g)	Run	Protein Extracted
1	13.37	21	14.2	41	13.02	61	13.22
2	11.04	22	13.43	42	13.72	62	14.64
3	12.68	23	12.96	43	13.26	63	12.97
4	12.49	24	14.03	44	12.33	64	11.4
5	11.91	25	13.46	45	14.25	65	14.34
6	14.54	26	13.45	46	14.29	66	12.23
7	13.9	27	14.32	47	12.13	67	14.24
8	14.5	28	12.23	48	11.7	68	14.73
9	14.24	29	13.71	49	14.02	69	12.55
10	12.17	30	14.39	50	13.01	70	14.16
11	14.36	31	13.59	51	12.12	71	14.5
12	14.26	32	13.96	52	14.03	72	12.12
13	13.9	33	12.57	53	12.64	73	11.05
14	13.95	34	14.43	54	14.13	74	12.9
15	14.29	35	11.55	55	14.12	75	12.93
16	13.72	36	10.78	56	13.5	76	13.1
17	12.76	37	12.82	57	14.44		
18	12.63	38	12.81	58	12.59		
19	12.98	39	14.19	59	12.92		
20	14.21	40	14.46	60	13.32		

Total mass of flour = 6080 g

Total mass of protein extracted= 1011.86 g

Appendix B: Rotational Steady State Data

Table B1 Mean Rotational Steady State Data for Emulsion 1

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
0.809513	0.010002	80.934	89.981	24.999	0.239469
0.527723	0.015847	33.30095	180.079	25.0025	0.239537
0.500988	0.025118	19.9453	270.1375	25.001	0.240408
0.61497	0.039815	15.4457	360.1735	25	0.240875
0.79668	0.063097	12.62635	450.2715	25.001	0.240983
0.951508	0.100001	9.515015	540.385	24.9995	0.240062
0.991048	0.158489	6.253115	630.436	25.001	0.241748
0.962545	0.251188	3.83198	720.487	24.9995	0.24049
0.881817	0.398107	2.21503	810.515	25.002	0.239752
0.992121	0.630955	1.572415	900.59	24.998	0.240541
1.10857	0.999999	1.108565	990.719	24.999	0.239049
1.222955	1.58488	0.771638	1080.825	25.002	0.241175
1.50473	2.51189	0.599043	1170.895	25.001	0.240852
1.68167	3.98109	0.422415	1260.94	25.0015	0.24102
1.67521	6.30958	0.265502	1351.025	24.9985	0.241247
1.68633	9.999995	0.168633	1441.06	24.9985	0.240137
1.82618	15.84895	0.115224	1531.16	25	0.23985
2.23759	25.1189	0.08908	1621.255	24.9995	0.240827
2.89275	39.8107	0.072663	1711.315	24.9995	0.24026
3.820315	63.0957	0.060548	1801.36	24.9985	0.237916
5.141785	100	0.051418	1891.37	24.998	0.235149
6.8175	158.489	0.043016	1981.42	25.0005	0.232671
8.85058	251.189	0.035235	2071.53	24.998	0.234062
11.36041	398.107	0.028536	2161.61	24.998	0.235548
15.21345	630.958	0.024112	2251.665	24.9995	0.232567
20.6107	1000	0.020611	2341.735	24.9965	0.216178

Table B2 Mean Rotational Steady State Data for Emulsion 2

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
1.095995	0.01	109.605	89.9654	24.9995	0.240704
0.982578	0.015857	61.9668	180.009	24.9975	0.243378
0.996434	0.025122	39.66405	270.0755	25.0015	0.244496
1.16272	0.039818	29.20095	360.111	25	0.243511
1.46081	0.063095	23.15235	450.217	25.003	0.24226
1.73378	0.099999	17.33795	540.318	25	0.240086
1.811425	0.158489	11.42935	630.353	25.0015	0.238108
1.60354	0.251189	6.383835	720.42	25.001	0.241558
1.41095	0.398103	3.544175	810.471	25	0.241315
1.56175	0.630957	2.47521	900.5145	25.002	0.243016
1.784545	0.999995	1.78455	990.62	25.0005	0.241413
2.203925	1.58488	1.39059	1080.7	24.999	0.240001
2.76878	2.5119	1.102265	1170.755	24.999	0.238614
3.362525	3.98108	0.844628	1260.81	25.004	0.240974
3.49141	6.30957	0.553351	1350.86	24.9995	0.24047
3.558175	10	0.355818	1440.97	25.0005	0.239449
3.7484	15.8489	0.236508	1531.09	25.0015	0.238934
4.29978	25.11885	0.171177	1621.185	25.002	0.23467
4.957685	39.8107	0.124532	1711.23	24.998	0.232204
5.88487	63.0957	0.093269	1801.31	25.0015	0.230371
7.19919	100	0.071992	1891.355	24.9965	0.225514
8.89759	158.489	0.05614	1981.465	25.0005	0.221819
10.8464	251.189	0.04318	2071.53	25.0025	0.218516
13.1432	398.107	0.033014	2161.63	24.998	0.217114
16.1445	630.957	0.025587	2251.695	24.999	0.206378
20.20475	1000	0.020205	2341.73	25.0005	0.181181

Table B3 Mean Rotational Steady State Data for Emulsion 3

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
0.700825	0.010002	70.0701	89.981	24.999	0.19273
0.757006	0.015851	47.7572	180.048	24.997	0.194271
0.8193	0.025115	32.62145	270.0985	25.0005	0.193324
0.914212	0.039811	22.96375	360.158	24.999	0.192616
1.01761	0.063094	16.12835	450.248	24.9985	0.193328
1.08466	0.099997	10.8469	540.3615	24.9985	0.195389
1.103055	0.158491	6.959745	630.3975	25.0015	0.181193
1.097085	0.251188	4.367585	720.4325	25	0.178875
1.01114	0.398105	2.539885	810.468	24.9995	0.176966
1.03556	0.630956	1.641255	900.527	25.001	0.176423
1.046572	1.000003	1.046572	990.602	25.0035	0.173123
1.07997	1.584905	0.681413	1080.65	25	0.170032
1.204245	2.511885	0.47942	1170.705	25.002	0.172713
1.18424	3.981085	0.297466	1260.765	24.998	0.173407
1.234255	6.309595	0.195616	1350.775	25.0005	0.172037
1.36647	9.999995	0.136648	1440.875	25.0005	0.173106
1.53687	15.849	0.09697	1530.945	25.001	0.17224
1.83621	25.1189	0.073101	1621.015	25	0.172716
2.52277	39.8107	0.063369	1711.07	24.9995	0.170702
3.020615	63.0958	0.047874	1801.115	24.9995	0.170595
3.54309	100	0.035431	1891.175	25	0.170123
4.219215	158.489	0.026621	1981.295	25.0015	0.167937
4.85833	251.189	0.019341	2071.375	24.999	0.16451
5.899055	398.107	0.014818	2161.42	25.003	0.149247
7.86547	630.9575	0.012466	2251.47	25.001	0.139465
10.5816	1000	0.010582	2341.535	25	0.116595

Table B4 Mean Rotational Steady State Data for Emulsion 4

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
2.32395	0.01	232.334	34.9597	24.9995	0.16108
2.16546	0.01585	136.649	69.9817	25.002	0.15865
2.05687	0.02512	81.8915	105.074	25.002	0.15531
1.93864	0.03981	48.698	140.12	25.0015	0.16203
1.84824	0.0631	29.2926	175.204	25.0005	0.16886
1.78668	0.1	17.867	210.25	25.0015	0.17514
1.79913	0.15849	11.352	245.303	25.002	0.17584
1.93298	0.25119	7.69536	280.371	25.0015	0.17873
1.99538	0.3981	5.01221	315.378	24.9995	0.1799
1.72366	0.63096	2.73179	350.486	24.9985	0.17598
1.42902	0.99999	1.42903	385.532	25	0.17853
1.80583	1.58492	1.13939	420.639	25.0005	0.17335
2.19731	2.51188	0.87477	455.685	25.002	0.17723
2.99152	3.98108	0.75144	490.738	25.0025	0.17531
4.04319	6.30963	0.6408	525.799	25.003	0.17738
5.75488	10	0.57549	560.821	24.996	0.17804
7.74188	15.8489	0.48848	595.937	24.999	0.17735
8.54558	25.1189	0.34021	630.998	24.9985	0.17345
8.88111	39.8108	0.22308	666.059	24.999	0.17124
9.66655	63.0957	0.15321	701.112	25.0025	0.17007
10.8467	100	0.10847	736.15	25.003	0.1699
12.3099	158.489	0.07767	771.266	24.996	0.16957
14.2158	251.189	0.05659	806.295	24.997	0.16708
16.7721	398.107	0.04213	841.419	24.999	0.16632
20.885	630.957	0.0331	876.457	24.999	0.16542
25.4337	1000	0.02543	911.502	25.001	0.15173

Table B5 Mean Rotational Steady State Data for Emulsion 5

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
0.339056	0.01	33.90635	89.9732	25.001	0.169967
0.372571	0.015852	23.50305	180.048	24.9985	0.170296
0.445451	0.025121	17.732	270.0985	25.0015	0.170224
0.512787	0.039809	12.8811	360.119	25	0.170122
0.580197	0.063093	9.19583	450.217	24.9985	0.169671
0.612458	0.100001	6.124515	540.315	24.999	0.17036
0.608994	0.158495	3.84237	630.382	24.9995	0.169948
0.616896	0.251186	2.455935	720.4405	25.002	0.16786
0.606229	0.398106	1.52278	810.484	25	0.170506
0.663884	0.63096	1.052182	900.543	24.9995	0.169475
0.738452	1.000003	0.738452	990.633	25.001	0.170478
0.802369	1.5849	0.506259	1080.74	24.9985	0.170922
0.836544	2.5119	0.333033	1170.795	24.9985	0.172164
0.900549	3.98107	0.226209	1260.865	25	0.172221
1.001708	6.30957	0.15876	1350.925	25.0005	0.171549
1.151875	9.999995	0.115187	1440.98	25.0015	0.171825
1.38595	15.84895	0.087447	1531.1	24.998	0.172611
1.761985	25.11885	0.070146	1621.2	24.9995	0.174387
2.31364	39.8107	0.058116	1711.27	25	0.173755
2.955145	63.09575	0.046836	1801.34	24.999	0.172648
3.82734	100	0.038273	1891.41	25.001	0.170149
4.940675	158.489	0.031174	1981.475	25.001	0.168881
6.4145	251.189	0.025537	2071.575	25.001	0.168535
8.38046	398.107	0.021051	2161.665	24.9995	0.168199
11.51137	630.9575	0.018244	2251.735	24.998	0.157512
15.62652	1000	0.015627	2341.825	25.0015	0.139833

Table B6 Mean Rotational Steady State Data for Emulsion 6

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
2.15318	0.01	215.229	34.9597	25	0.5323
1.94478	0.01585	122.714	69.9895	25.0015	0.52246
1.98955	0.02512	79.2094	105.106	25.001	0.52634
2.07849	0.03982	52.193	140.135	25.001	0.53486
2.08984	0.0631	33.1201	175.22	24.999	0.54674
2.10073	0.1	21.0077	210.265	25.0025	0.55933
2.24693	0.15849	14.1772	245.318	25.0035	0.51784
2.3799	0.25119	9.47462	280.379	25.001	0.41965
2.31736	0.39811	5.82088	315.409	25	0.32406
2.13155	0.63096	3.37827	350.522	25.002	0.26039
2.06009	1	2.06008	385.564	25.0005	0.51688
2.01627	1.58491	1.27217	420.668	25	0.3595
2.69531	2.51189	1.07303	455.744	25.0015	0.42963
3.80753	3.98105	0.95642	490.774	24.9995	0.42583
4.87038	6.30959	0.7719	525.882	25.0025	0.43881
6.01786	10	0.60179	560.936	24.9995	0.45081
7.22528	15.849	0.45588	595.989	24.999	0.4364
7.34965	25.1189	0.29259	631.019	25.0015	0.43105
8.02976	39.8107	0.2017	666.095	25.0005	0.41977
8.98208	63.0957	0.14236	701.156	25	0.41701
10.129	100	0.10129	736.241	25.0015	0.26342
11.647	158.489	0.07349	771.31	24.998	0.29125
13.7819	251.189	0.05487	806.332	25.0005	0.37007
16.5072	398.107	0.04146	841.424	25	0.37168
20.1513	630.958	0.03194	876.485	24.9965	0.38085
25.5595	1000	0.02556	911.562	25.0005	0.42518

Table B7 Mean Rotational Steady State Data for Emulsion 7

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
1.588395	0.010003	158.803	89.981	24.9975	0.237261
1.30872	0.015848	82.57345	180.0565	25.0005	0.238062
1.48675	0.025122	59.18065	270.1075	24.999	0.237055
1.98769	0.039807	49.93225	360.112	24.999	0.237595
2.50447	0.063099	39.6899	450.2025	24.9975	0.236348
2.732435	0.099999	27.3245	540.308	25.0015	0.236916
2.67342	0.15849	16.86815	630.351	24.9975	0.237368
2.382265	0.251187	9.48406	720.418	25.0015	0.239917
2.1713	0.398108	5.45404	810.4845	24.997	0.236489
2.15223	0.630957	3.411055	900.5435	24.999	0.239264
2.40144	1.000005	2.40143	990.642	25	0.236933
2.80483	1.58489	1.76973	1080.755	25.001	0.237484
3.60847	2.511875	1.43656	1170.795	24.999	0.23551
4.452125	3.981065	1.118325	1260.85	25.0015	0.235783
5.196865	6.30958	0.823647	1350.87	25.0015	0.232861
5.45409	9.999985	0.54541	1440.94	25.0005	0.234262
5.935545	15.8489	0.374508	1531.07	24.9975	0.234361
6.70779	25.11885	0.267042	1621.18	25.002	0.23252
7.60312	39.8107	0.190982	1711.255	25.001	0.229422
8.760315	63.0958	0.138842	1801.315	25.0005	0.230695
10.22955	100	0.102296	1891.37	24.999	0.230423
12.25185	158.489	0.077304	1981.455	25.0005	0.228957
15.02415	251.189	0.059812	2071.56	25	0.228019
18.4586	398.107	0.046366	2161.655	25.002	0.22684
23.4361	630.957	0.037144	2251.715	25.0005	0.221403
30.68135	1000	0.030681	2341.775	25.001	0.213324

Table B8 Mean Rotational Steady State Data for Emulsion 8

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
1.515485	0.010002	151.517	89.9732	24.999	0.221342
1.396645	0.015848	88.13395	180.048	24.9995	0.21909
1.579195	0.025122	62.86025	270.122	24.9995	0.215453
1.863145	0.039807	46.80585	360.189	24.9985	0.211069
2.23755	0.063097	35.46195	450.279	25.0005	0.207397
2.477485	0.100004	24.7738	540.4085	25	0.203656
2.479455	0.158491	15.6441	630.4675	24.998	0.201878
2.251915	0.25119	8.96497	720.534	25.003	0.202131
2.11418	0.398106	5.310595	810.6085	24.998	0.196261
2.040605	0.630959	3.23414	900.6205	24.999	0.196246
2.231705	0.999995	2.23172	990.6875	25.002	0.192671
2.53005	1.5849	1.59635	1080.81	24.997	0.189334
3.010835	2.5119	1.198625	1170.89	25.0015	0.184909
3.36162	3.981085	0.844399	1260.97	24.9985	0.183642
3.44955	6.309555	0.546719	1351.025	24.9985	0.182307
3.64349	10	0.364349	1441.055	25.0005	0.187131
4.297865	15.8489	0.271177	1531.165	25.001	0.197145
4.93753	25.11885	0.196567	1621.285	25.0005	0.197595
5.75672	39.8107	0.144602	1711.345	24.9995	0.195048
6.98294	63.09575	0.110672	1801.415	25.0015	0.195214
8.130535	100	0.081305	1891.505	25.001	0.193811
9.67571	158.4895	0.061049	1981.52	24.999	0.192409
11.7405	251.189	0.04674	2071.58	24.9995	0.188877
14.4628	398.107	0.036329	2161.7	25.0015	0.179415
18.08345	630.957	0.02866	2251.76	24.9985	0.166416
22.89995	1000	0.0229	2341.84	24.9995	0.140032

Table B9 Mean Rotational Steady State Data for Emulsion 9

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
1.132755	0.01	113.2725	90.0032	25.0015	0.244073
0.848652	0.015845	53.56085	180.0595	25.0015	0.245819
0.882012	0.025115	35.11925	270.118	25.001	0.247917
1.122955	0.039809	28.2088	360.138	25.0005	0.24959
1.46321	0.063095	23.1906	450.2205	25.001	0.248623
1.68106	0.100001	16.8105	540.3265	24.9985	0.249165
1.699995	0.158489	10.7263	630.37	25.0015	0.249223
1.533395	0.251198	6.10432	720.452	25.0025	0.248839
1.267915	0.398107	3.184855	810.519	24.9995	0.250269
1.496425	0.63096	2.371665	900.531	25	0.250288
1.6465	0.999999	1.6465	990.6525	24.999	0.249057
1.97292	1.584905	1.24482	1080.755	25.0015	0.249246
2.582245	2.51188	1.028015	1170.8	24.9965	0.248867
3.061265	3.98108	0.768954	1260.86	25.003	0.248761
3.050145	6.309555	0.483417	1350.925	24.9985	0.249528
3.120735	10	0.312073	1440.98	24.9975	0.250973
3.34223	15.84895	0.210881	1531.08	25.0045	0.251293
3.742095	25.1189	0.148976	1621.18	25	0.250068
4.285285	39.8107	0.107642	1711.235	24.9975	0.249034
5.051595	63.09575	0.080062	1801.325	25.0015	0.248208
6.17272	100	0.061727	1891.37	24.9975	0.248255
7.651635	158.489	0.048279	1981.41	25.0015	0.247872
9.659945	251.1885	0.038457	2071.5	24.999	0.247424
12.324	398.1075	0.030956	2161.575	25.0015	0.245029
15.87045	630.957	0.025153	2251.61	25.001	0.241097
21.26575	1000	0.021266	2341.685	25.003	0.221192

Table B10 Mean Rotational Steady State Data for Emulsion 10

Stress	Shear rate	Viscosity	Step time	Temperature	Normal stress
Pa	1/s	Pa.s	s	°C	Pa
2.22528	0.01001	222.39	34.9753	25.001	0.18084
2.01712	0.01586	127.195	70.0675	25.002	0.17763
1.91254	0.02512	76.1439	105.184	25.001	0.17457
1.80319	0.03981	45.2953	140.244	24.9995	0.17661
1.61561	0.06311	25.6006	175.329	25.0035	0.18332
1.48662	0.1	14.8663	210.39	25.003	0.18692
1.49445	0.15849	9.42898	245.459	25	0.19006
1.61368	0.25119	6.42412	280.551	25.0005	0.19194
1.69186	0.39811	4.24973	315.573	24.9995	0.18764
1.54928	0.63096	2.45543	350.674	25.002	0.18707
1.33873	1	1.33874	385.727	24.999	0.18886
1.43842	1.5849	0.90758	420.796	24.9975	0.18808
1.73976	2.51187	0.69261	455.865	25.0025	0.18644
2.43931	3.98107	0.61273	490.855	25.0025	0.18698
3.62794	6.30961	0.57499	525.979	25.001	0.19082
4.72827	10	0.47283	561.017	25.001	0.19331
5.96467	15.849	0.37634	596.086	25.0015	0.19347
6.39995	25.1189	0.25479	631.162	25.001	0.18986
6.8859	39.8107	0.17297	666.193	24.996	0.17549
7.68108	63.0957	0.12174	701.295	25	0.17796
8.64793	100	0.08648	736.379	25.0025	0.17554
9.62296	158.489	0.06072	771.456	25.0035	0.17433
11.0321	251.189	0.04392	806.525	25.0005	0.17403
12.8869	398.107	0.03237	841.601	24.9985	0.17035
15.7853	630.957	0.02502	876.694	24.9985	0.1653
20.4047	1000	0.0204	911.755	24.998	0.15664

Appendix C: Mean Amplitude Oscillatory Sweep Data

Table C14 Mean Amplitude Oscillatory Sweep Data for Emulsion 1

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.110959	110.305	13.59975	0.12319	111.1405	17.68855	7.02282	0.099833
0.17641	109.8	13.3254	0.121254	110.606	17.6035	6.91355	0.159491
0.271996	106.6045	13.7273	0.128751	107.4845	17.10665	7.336525	0.253051
0.40034	98.4123	13.9441	0.141647	99.39555	15.8193	8.062135	0.402764
0.523263	78.4728	13.8364	0.176267	79.68345	12.682	9.996625	0.65663
0.508194	44.5398	11.6935	0.263241	46.0509	7.32923	14.7469	1.10444
0.522849	28.7754	9.43899	0.329182	30.28635	4.820225	18.2176	1.727025
0.652858	22.26015	8.35343	0.376703	23.77855	3.78448	20.63665	2.74657
0.763413	15.4378	6.914695	0.450438	16.91935	2.692795	24.23725	4.51672
0.843266	10.00495	5.45173	0.546414	11.39545	1.813645	28.64415	7.393545
0.940772	6.755885	4.749175	0.703228	8.258215	1.314335	35.1152	11.3904
1.1543	5.286745	4.353075	0.826608	6.84878	1.090016	39.5703	17.00985
1.29649	3.269185	2.93939	0.897829	4.39747	0.69988	41.8913	29.46405
1.483265	2.637215	2.151225	0.81362	3.40587	0.542061	39.06285	43.5923
2.07676	2.49313	2.16235	0.865557	3.30261	0.525627	40.80625	62.86495
3.341135	2.376025	2.41251	1.013779	3.387595	0.539153	45.34075	98.6394
5.03633	2.07963	2.421855	1.162495	3.194325	0.508392	49.2092	157.6585

7.04101	1.72412	2.118015	1.227865	2.732635	0.434913	50.7578	257.506
9.210905	1.483255	1.70093	1.14666	2.258135	0.359393	48.83165	407.705
12.05805	1.338665	1.329335	0.992909	1.887565	0.300416	44.73635	638.701
16.17565	1.253925	1.01824	0.811988	1.6159	0.257179	39.04055	1000.879

Table C2 Mean Amplitude Oscillatory Sweep Data for Emulsion 2

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.14133	140.307	22.2072	0.1607	142.086	22.6136	9.12492	0.09942
0.22618	141.39	21.7886	0.15524	143.068	22.77	8.82324	0.15803
0.36066	141.42	22.0319	0.15723	143.141	22.7816	8.93359	0.25194
0.56857	140.851	22.0427	0.15791	142.58	22.6924	8.97136	0.39861
0.88431	137.783	22.4864	0.16455	139.62	22.2212	9.34244	0.63334
1.31408	127.46	22.8788	0.18058	129.506	20.6115	10.2346	1.01466
1.23904	77.018	20.0285	0.26644	79.6201	12.672	14.9031	1.54558
1.3163	48.9808	16.68	0.34787	51.7805	8.24112	19.1517	2.54425
1.40063	30.9165	14.4329	0.47239	34.1362	5.43294	25.2586	4.11891
1.5563	19.3926	12.8574	0.6662	23.2701	3.70355	33.6635	6.72549
1.91671	11.0596	10.7224	0.96893	15.404	2.45163	44.0957	12.5045
2.38311	5.59679	7.44291	1.33524	9.32881	1.48473	52.9018	25.3417
3.04437	3.21987	4.68194	1.48827	5.6945	0.90631	55.7377	54.7548
3.08105	2.62426	3.73333	1.42964	4.56964	0.72728	54.8051	67.1018

3.2515	2.24214	3.0253	1.35168	3.77171	0.60029	53.2544	85.9376
3.73123	1.96582	2.477	1.26456	3.16946	0.50444	51.3364	117.368
4.63354	1.71758	2.13502	1.24146	2.74408	0.43673	50.9441	168.364
6.44293	1.5677	1.89942	1.20959	2.4665	0.39255	50.2118	260.714
8.80693	1.42433	1.56781	1.09894	2.1226	0.33782	47.4367	414.124
11.1614	1.30617	1.12831	0.86307	1.73016	0.27536	40.5602	644.697
14.7504	1.23214	0.80877	0.65575	1.47729	0.23512	33.0807	998.071

Table C3 Mean Amplitude Oscillatory Sweep Data for Emulsion 3

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.069448	69.3132	9.82409	0.142597	70.0062	11.14183	8.11541	0.09907
0.108953	67.58105	10.11643	0.151438	68.3352	10.87588	8.610965	0.159425
0.156856	60.72135	10.1489	0.170157	61.56625	9.798555	9.65585	0.255314
0.202732	47.9137	9.84497	0.209364	48.91765	7.785465	11.8232	0.414583
0.178766	23.0116	7.678695	0.329515	24.2664	3.86212	18.2259	0.731832
0.194743	16.46125	6.224745	0.37494	17.6021	2.80147	20.54485	1.107385
0.239987	12.51105	5.361625	0.426644	13.61215	2.166445	23.10275	1.767355
0.283588	8.736955	4.40153	0.503235	9.78305	1.55702	26.71295	2.908095
0.317083	5.857975	3.37054	0.571309	6.75953	1.075812	29.72875	4.69574
0.369136	4.544245	2.847895	0.626198	5.365025	0.85387	32.0262	6.864215
0.400905	2.87528	1.958395	0.674481	3.481855	0.554154	33.9315	11.52465
0.501545	2.516605	1.75451	0.68309	3.07408	0.489255	34.172	16.41655
0.638198	2.04666	1.240505	0.605507	2.3937	0.380969	31.18215	26.6121
0.854169	1.847255	1.019473	0.55109	2.11049	0.335895	28.8412	40.4561
1.24826	1.72209	0.961538	0.555401	1.974465	0.314246	28.97925	63.21075
1.904945	1.633485	1.000798	0.609487	1.918225	0.305296	31.26915	99.3038
2.888775	1.524945	1.00906	0.658852	1.83134	0.291467	33.2643	157.724
4.246265	1.408985	0.929263	0.657396	1.69056	0.269061	33.19905	251.137
6.175085	1.32017	0.810832	0.612713	1.5523	0.247056	31.36025	397.6985

9.03589	1.25554	0.676577	0.53777	1.42957	0.227524	28.12605	632.069
13.3419	1.211335	0.542575	0.447489	1.33021	0.211709	23.9958	1003.025

Table C4 Mean Amplitude Oscillatory Sweep Data for Emulsion 4

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.53423	526.248	91.9532	0.17443	534.224	85.0243	9.89419	0.1
0.84785	525.693	91.9839	0.17484	533.68	84.9378	9.91717	0.15886
1.34064	524.155	91.427	0.17427	532.07	84.6816	9.88581	0.25196
2.09427	516.181	92.232	0.17857	524.357	83.454	10.1249	0.3994
3.22796	499.225	92.3011	0.18485	507.686	80.8006	10.4731	0.6359
4.64281	448.003	89.9236	0.20138	456.943	72.7248	11.3856	1.01715
5.01588	304.8	82.8484	0.29759	316.422	50.3601	16.5031	1.56173
3.79432	157.898	72.2179	0.45644	173.63	27.6341	24.5335	2.22372
4.282	90.021	55.5248	0.62113	105.776	16.8347	31.8403	4.0396
6.9208	15.9385	25.5678	1.6782	30.2208	4.80979	58.6266	24.2596
13.1058	1.55349	7.0006	4.50537	7.17099	1.1413	77.4791	181.541
13.1502	1.52582	5.92686	3.884	6.12017	0.97406	75.5576	213.819
15.2859	1.45977	4.87697	3.32626	5.09193	0.8104	73.1781	302.423
20.0971	1.44077	4.26022	2.95812	4.49863	0.71598	71.2185	445.7
24.3828	1.46343	3.82673	2.64666	4.10334	0.65307	68.8417	585.84
25.5748	1.39221	3.74631	2.694	3.99937	0.63652	69.4179	642.336

25.9318	1.35272	3.24127	2.39676	3.51748	0.55982	66.9418	741.083
27.381	1.31517	3.15281	2.39401	3.41812	0.54401	67.1711	806.414
27.051	1.30315	2.9368	2.2516	3.2144	0.51159	65.9341	846.444
26.002	1.30751	2.64699	2.2269	2.95775	0.47074	63.2826	899.98
27.2313	1.25931	2.35347	1.86899	2.67162	0.4252	61.6582	1018.91

Table C5 Mean Amplitude Oscillatory Sweep Data for Emulsion 5

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.047275	47.3423	6.783545	0.143106	47.8259	7.611725	8.144045	0.098854
0.075822	47.08505	7.387235	0.156105	47.6627	7.58575	8.871905	0.159017
0.119302	46.78925	7.162625	0.152751	47.3346	7.53354	8.684705	0.251885
0.183898	45.3001	7.39891	0.163292	45.9004	7.305275	9.274085	0.400687
0.271189	42.02515	7.19104	0.170851	42.63615	6.785755	9.695295	0.636109
0.372959	36.11515	6.84759	0.189375	36.75875	5.85034	10.72325	1.01458
0.464715	27.8154	6.074915	0.218185	28.47115	4.531325	12.30805	1.63255
0.528666	19.5045	5.05803	0.259025	20.1498	3.20694	14.5217	2.625105
0.591215	13.47435	4.366105	0.323567	14.16435	2.25433	17.9292	4.174085
0.653954	9.33331	3.998095	0.427611	10.15557	1.61631	23.14245	6.443415
0.74343	6.40861	3.664345	0.571213	7.38698	1.175675	29.6937	10.0688
0.869839	4.35286	3.20394	0.735076	5.407665	0.860657	36.2751	16.0864
1.016608	3.11323	2.63491	0.845666	4.07907	0.649204	40.2088	24.9283

1.23177	2.27352	1.972235	0.867481	3.00975	0.479017	40.941	40.9247
1.483925	1.794335	1.42343	0.79331	2.29037	0.364524	38.4253	64.79005
1.92359	1.550565	1.10889	0.714988	1.906405	0.303414	35.5588	100.9045
2.641425	1.40022	0.898005	0.64109	1.66369	0.264785	32.65245	158.77
3.80908	1.30755	0.744203	0.568958	1.504815	0.239499	29.62445	253.118
5.57471	1.24693	0.621347	0.498172	1.39348	0.22178	26.4683	400.042
8.360655	1.20946	0.519761	0.429689	1.316635	0.209549	23.2443	634.985
12.72915	1.188505	0.42774	0.359882	1.26322	0.201048	19.79	1007.66

Table C6 Mean Amplitude Oscillatory Sweep Data for Emulsion 6

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.30173	298.473	44.9972	0.1505	301.864	48.0432	8.55784	0.09996
0.47817	297.575	46.408	0.15573	301.184	47.9349	8.85094	0.15877
0.75658	296.271	47.0394	0.15856	299.991	47.7451	9.00939	0.25221
1.18691	292.825	46.9979	0.16029	296.579	47.202	9.10587	0.40016
1.82634	283.395	47.5686	0.1677	287.362	45.735	9.51975	0.6356
2.6388	255.541	47.2481	0.18496	259.872	41.3599	10.479	1.01579
2.59553	149.774	41.2464	0.27593	155.352	24.7249	15.4255	1.66652
2.16215	83.7018	34.8537	0.42456	90.8353	14.4569	22.914	2.36924
2.54574	55.88	28.6699	0.51809	62.8381	10.001	27.357	4.04166

3.33457	20.3579	19.2076	1.10419	28.3569	4.51314	46.1144	13.8817
5.96513	4.96394	7.85009	1.59931	9.28806	1.47824	57.9778	137.082
9.04322	1.55291	2.99677	1.96729	3.39275	0.53997	61.9211	268.547
9.12452	1.55775	2.7498	1.78654	3.17283	0.50497	59.9722	288.689
10.5138	1.49798	2.37299	1.59483	2.81535	0.44808	57.3259	374.118
8.23242	1.7788	2.89342	1.65369	3.40182	0.54142	58.5424	244.675
5.22557	1.93473	2.95649	1.54981	3.54363	0.56399	56.6564	146.312
5.38192	1.75767	2.58858	1.48197	3.1335	0.49871	55.7431	171.562
7.37599	1.5747	2.24815	1.43294	2.74788	0.43734	54.9063	268.319
10.3846	1.45485	1.95474	1.3475	2.44138	0.38856	53.1266	425.316
14.4717	1.36354	1.61329	1.18798	2.11861	0.33719	49.5094	682.293
17.2766	1.26444	1.19074	0.93962	1.74431	0.27761	42.7558	1000

Table C7 Mean Amplitude Oscillatory Sweep Data for Emulsion 7

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.29028	286.367	42.0846	0.14686	289.444	46.0664	8.35448	0.10028
0.45803	285.916	41.7949	0.14621	288.954	45.9885	8.31815	0.15852
0.7254	283.537	42.1428	0.14862	286.652	45.622	8.45365	0.25305
1.1183	275.832	42.5279	0.15418	279.091	44.4187	8.7649	0.40068
1.64078	252.648	42.4382	0.16794	256.188	40.7736	9.53299	0.64041
1.97607	181.03	38.397	0.21209	185.057	29.4527	11.9745	1.06793
1.64047	89.5438	30.6689	0.34377	94.658	15.0653	18.9682	1.73074
1.81108	61.8363	27.6681	0.44762	67.7444	10.7819	24.1139	2.67418
1.93016	40.5843	24.5915	0.60613	47.4537	7.55248	31.2209	4.06783
2.29926	28.7443	22.7352	0.79135	36.6492	5.8329	38.3551	6.27464
2.78242	16.0063	18.0203	1.12674	24.1031	3.83613	48.407	11.5513
3.29206	8.46631	13.4588	1.58881	15.9046	2.53129	57.7644	20.6904
3.66287	5.01965	9.77517	1.95068	10.9923	1.74948	62.7848	33.284
4.2371	3.29601	7.38368	2.24291	8.08746	1.28716	65.9221	52.3411
4.93481	2.52705	5.61226	2.22191	6.15574	0.97972	65.7365	80.1045
5.88507	2.27932	4.49592	1.9726	5.04122	0.80233	63.0942	116.682
7.70511	2.14703	3.91112	1.82112	4.46196	0.71014	61.2154	172.656
11.0562	1.91026	3.56939	1.86789	4.04856	0.64435	61.8294	273.065

16.3239	1.51423	2.78512	1.8392	3.17037	0.50458	61.4513	514.621
20.906	1.30299	1.84371	1.41501	2.25766	0.35932	54.7508	926.463
21.52	1.28762	1.73681	1.34652	2.16356	0.34255	53.3112	1000

Table C8 Mean Amplitude Oscillatory Sweep Data for Emulsion 8

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.204723	202.8215	26.1701	0.129033	204.503	32.54765	7.352425	0.100108
0.323689	202.2075	26.33645	0.130262	203.9165	32.45425	7.421605	0.158737
0.512096	200.957	26.3114	0.130935	202.672	32.2562	7.459595	0.252675
0.792959	196.337	26.66675	0.135836	198.14	31.53495	7.73545	0.400203
1.194725	185.313	26.86805	0.145059	187.2515	29.802	8.253595	0.638018
1.581015	146.999	26.05835	0.177969	149.3	23.76175	10.08998	1.060015
0.840297	51.83165	19.2565	0.377248	55.3185	8.80421	20.6486	1.520455
1.23759	43.307	18.56915	0.430856	47.1272	7.500525	23.3016	2.62703
1.322355	27.79295	16.65725	0.600088	32.40315	5.157125	30.96565	4.087825
1.5399	18.72175	15.0419	0.803854	24.016	3.82226	38.7938	6.41818
1.804625	11.1476	12.41435	1.11407	16.68495	2.65549	48.088	10.80115
2.101495	6.413495	9.60072	1.49831	11.54615	1.837635	56.2751	18.17005
2.364145	4.06006	7.09221	1.7472	8.17214	1.300635	60.2152	28.89725
2.69784	2.888495	5.311925	1.83855	6.04653	0.962336	61.45615	44.5913
3.287585	2.298255	4.07893	1.77481	4.68214	0.745186	60.5882	70.1903

4.13472	2.069	3.238975	1.56633	3.84392	0.611779	57.42035	107.5525
5.54603	1.933905	2.75359	1.423795	3.36493	0.535545	54.91405	164.8025
7.717215	1.72694	2.4055	1.392835	2.961235	0.471295	54.32175	260.596
9.8883	1.46778	1.818935	1.23926	2.33729	0.371992	51.0984	423.0665
11.99255	1.31825	1.307875	0.992158	1.857035	0.295556	44.77005	645.79
15.5836	1.24004	0.964545	0.777853	1.571105	0.25005	37.8716	991.8865

Table C9 Mean Amplitude Oscillatory Sweep Data for Emulsion 9

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.207462	205.3205	30.15185	0.14677	207.523	33.02825	8.34968	0.099908
0.32869	204.585	30.70755	0.150486	206.8765	32.92545	8.55794	0.158871
0.519747	203.2865	30.98185	0.152901	205.634	32.72765	8.693215	0.252901
0.805239	198.562	31.34455	0.158531	201.0215	31.9935	9.008105	0.400776
1.193418	183.698	31.03195	0.170783	186.3035	29.6511	9.691305	0.641799
1.443031	132.6568	28.25125	0.227062	135.6819	21.59445	12.7808	1.08431
1.456305	82.4921	24.3087	0.316672	86.0543	13.69595	17.5412	1.70441
1.394159	49.6475	21.85255	0.445518	54.24695	8.633695	24.0105	2.60317
1.574059	33.24945	19.72	0.599123	38.65975	6.15289	30.9222	4.09154
1.835125	21.6425	17.28565	0.798695	27.69825	4.40831	38.61415	6.58834
2.22302	12.22153	13.56302	1.09549	18.2607	2.906275	47.58135	11.83935
2.68036	6.503795	9.786905	1.467545	11.7709	1.873395	55.4217	21.71905

3.01051	4.010385	7.168045	1.746345	8.236285	1.310847	59.62405	35.00585
3.361675	2.923285	5.52075	1.843965	6.266595	0.99736	60.83125	51.92895
3.92239	2.33894	4.235495	1.773465	4.8574	0.773079	59.75545	78.4332
4.73024	2.10782	3.435265	1.59952	4.048895	0.644402	57.1213	114.546
6.117915	1.95373	2.994865	1.50887	3.590935	0.571515	55.7174	168.628
8.54019	1.73181	2.652085	1.505255	3.18375	0.50671	55.49475	266.3425
11.49782	1.4493	1.959375	1.337956	2.45621	0.390918	52.0215	457.992
13.2928	1.30437	1.336245	1.020318	1.878605	0.298989	44.8738	697.9735
16.07765	1.236365	0.967653	0.780105	1.57867	0.251253	37.4678	1016.628

Table C10 Mean Amplitude Oscillatory Sweep Data for Emulsion 10

Oscillation stress	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation strain
Pa	Pa	Pa		Pa	Pa.s	°	%
0.44743	440.057	76.6876	0.17428	446.689	71.0928	9.88614	0.10017
0.70813	438.615	77.9148	0.17763	445.482	70.9006	10.0724	0.15896
1.121	436.78	78.5299	0.17981	443.784	70.6304	10.1932	0.2526
1.75823	432.311	77.5165	0.17932	439.206	69.9018	10.1663	0.40031
2.70712	418.733	77.9342	0.18613	425.924	67.7879	10.5437	0.63559
3.99206	387.812	76.1431	0.19635	395.216	62.9006	11.1088	1.0101
5.40065	322.785	71.2738	0.22101	330.564	52.6109	12.4624	1.6342
5.16901	190.135	63.3103	0.33507	200.488	31.9087	18.5069	2.57774
4.40977	98.7097	55.1965	0.57073	113.355	18.0411	29.5632	3.88584
5.68788	36.4329	42.7494	1.18279	56.1955	8.94378	49.7208	10.2177
15.8638	2.69943	9.84002	3.71149	10.2044	1.62408	74.8852	181.969
16.8688	1.85708	6.92307	3.74211	7.17052	1.14123	74.8785	237.039
18.1376	1.81353	6.0182	3.32696	6.28646	1.00052	73.2129	288.488
18.2595	1.90387	5.7869	3.05858	6.09306	0.96974	71.8363	302.2
19.7639	1.84367	5.44579	2.96139	5.74976	0.9151	71.3211	345.693
20.5615	2.09188	5.50487	2.69787	5.89483	0.93819	69.356	291.005
18.6436	1.8464	4.56975	2.51121	4.93414	0.78529	67.976	396.059

20.0392	1.57735	3.94202	2.50256	4.2462	0.6758	68.199	548.311
25.4523	1.36345	3.28402	2.41087	3.55628	0.566	67.4353	728.952
28.9194	1.3326	2.71776	2.02817	3.03194	0.48255	63.3552	886.16
27.2767	1.31664	2.56699	1.9346	2.89295	0.46043	62.0371	1000

Appendix D: Mean Oscillatory Frequency Sweep Data

Table D1 Mean Oscillatory Frequency Sweep Data for Emulsion 1

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	80.96145	21.0575	0.261557	83.6675	8366.745	14.65325	0.156087	0.186505
0.015849	95.21115	25.2684	0.272182	98.66745	6225.475	15.17495	0.193635	0.196517
0.025119	111.4895	23.88885	0.21466	114.0245	4539.395	12.11435	0.223425	0.195848
0.039811	123.6235	24.70685	0.200131	126.089	3167.215	11.3134	0.245797	0.194893
0.063096	135.548	24.8723	0.183212	137.843	2184.66	10.37725	0.272758	0.197883
0.1	142.4255	26.6273	0.18679	144.9015	1449.01	10.57918	0.290987	0.200802
0.15849	151.3405	26.56875	0.175315	153.6615	969.5375	9.942875	0.308672	0.200858
0.251189	160.6315	25.03565	0.155442	162.5835	647.2575	8.83402	0.325558	0.200227
0.398107	168.8775	25.0781	0.148846	170.735	428.867	8.465515	0.34232	0.200466
0.630957	177.481	26.102	0.146963	179.3905	284.3145	8.36046	0.358057	0.199616
1	183.2265	31.66745	0.171999	185.983	185.9825	9.755055	0.371652	0.199873
1.5849	193.9775	23.826	0.122716	195.436	123.3115	6.99604	0.391478	0.200242
2.51189	202.355	24.1959	0.119864	203.8005	81.13405	6.83486	0.406754	0.199579
3.98105	209.229	31.1012	0.147794	211.558	53.1413	8.404635	0.423072	0.199999
6.30957	218.7465	29.8743	0.13617	220.783	34.99175	7.753865	0.441842	0.200116
10.0001	229.227	30.2454	0.13146	231.2225	23.12205	7.488575	0.461516	0.199608

15.849	241.4295	31.52865	0.1302	243.4855	15.3628	7.4178	0.487871	0.20035
25.1188	261.1035	33.23905	0.126841	263.2195	10.479	7.22838	0.526176	0.1999
39.8105	297.0045	35.4496	0.118919	299.122	7.513655	6.78123	0.597793	0.199854
63.0957	373.089	38.36665	0.102473	375.069	5.94445	5.850435	0.748175	0.199481
100	551.994	42.12105	0.07609	553.613	5.536125	4.351025	1.110105	0.200501

Table D2 Mean Oscillatory Frequency Sweep Data for Emulsion 2

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	75.9824	23.2771	0.306415	79.47495	7947.49	17.03275	0.148915	0.187373
0.015849	100.3087	26.1603	0.259065	103.7599	6546.795	14.4964	0.19881	0.191718
0.025119	121.708	28.6464	0.232703	125.0635	4978.875	13.0934	0.245944	0.196772
0.039811	132.029	31.71425	0.233534	135.885	3413.275	13.12465	0.268546	0.197183
0.063096	145.3485	33.501	0.22538	149.21	2364.825	12.692	0.298137	0.199893
0.1	158.459	31.89285	0.196006	161.695	1616.95	11.08128	0.323128	0.199648
0.15849	169.6835	33.00925	0.187582	172.9635	1091.325	10.61136	0.345956	0.199893
0.251189	180.903	32.7707	0.177931	183.8675	731.9905	10.08679	0.36736	0.199876
0.398107	190.9725	34.5645	0.176656	194.1135	487.592	10.01411	0.387674	0.199427
0.630957	200.769	33.9377	0.164562	203.657	322.7745	9.34105	0.409136	0.200882
1	210.6055	36.80645	0.173407	213.801	213.801	9.837295	0.428219	0.200347
1.5849	220.7265	38.988	0.171674	224.196	141.4575	9.73641	0.448551	0.200064

2.51189	232.665	37.1409	0.158479	235.6135	93.79925	9.005055	0.4706	0.199675
3.98105	243.5465	38.8532	0.157071	246.639	61.9532	8.92556	0.493252	0.200134
6.30957	255.9685	40.2574	0.154859	259.128	41.06905	8.8019	0.518612	0.200004
10.0001	269.565	41.9924	0.153715	272.8255	27.2824	8.73816	0.545031	0.199827
15.849	285.9765	44.1177	0.151918	289.3725	18.2581	8.63733	0.578978	0.200082
25.1188	309.947	46.75595	0.147969	313.4775	12.47979	8.415595	0.626972	0.199996
39.8105	351.864	49.9305	0.138884	355.4235	8.92789	7.90531	0.71048	0.199875
63.0957	437.263	53.80415	0.120103	440.6165	6.9833	6.84679	0.879228	0.199513
100	631.2055	58.72925	0.0909	634.0145	6.340145	5.192505	1.261235	0.199064

Table D3 Mean Oscillatory Frequency Sweep Data for Emulsion 4

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	171.7185	43.0353	0.250077	177.03	17703	14.04015	0.32468	0.183656
0.015849	217.5185	54.39495	0.248412	224.2255	14147.65	13.9493	0.431265	0.19248
0.025119	256.5055	63.46265	0.244962	264.2565	10520.24	13.76235	0.517254	0.195932
0.039811	284.581	70.2185	0.243198	293.149	7363.57	13.66555	0.58235	0.198801
0.063096	316.503	67.25415	0.211995	323.57	5128.24	11.96915	0.641254	0.198482
0.1	340.3575	72.25255	0.211219	347.9455	3479.455	11.9264	0.693948	0.199422
0.15849	364.9585	73.30125	0.198788	372.2585	2348.785	11.2424	0.739647	0.198655
0.251189	385.6685	81.29485	0.208792	394.154	1569.155	11.79275	0.792599	0.201216
0.398107	411.8155	79.31345	0.190112	419.401	1053.491	10.7632	0.836569	0.199444
0.630957	433.3145	87.55	0.198171	442.1155	700.706	11.20665	0.887043	0.200532
1	461.049	88.2285	0.195536	469.465	469.4645	11.0612	0.938136	0.199819
1.5849	486.482	90.8308	0.185142	494.897	312.258	10.4887	0.994023	0.200679
2.51189	514.6115	94.61395	0.184647	523.2385	208.3045	10.4616	1.041955	0.199365
3.98105	543.0675	100.2668	0.182634	552.2605	138.7225	10.34947	1.103782	0.199753
6.30957	571.2935	108.9793	0.190611	581.595	92.1766	10.79175	1.164784	0.200205
10.0001	604.7855	113.326	0.187094	615.312	61.5308	10.59715	1.230898	0.200059
15.849	641.5345	120.6924	0.187737	652.7895	41.188	10.63275	1.306046	0.200035
25.1188	687.8725	128.9868	0.187035	699.863	27.8621	10.59385	1.39923	0.199928
39.8105	753.158	139.2195	0.184038	765.921	19.2392	10.4278	1.531945	0.200008

63.0957	864.3445	151.6175	0.173881	877.5605	13.9084	9.863585	1.75404	0.199858
100	1086.466	166.549	0.151109	1099.227	10.99227	8.59176	2.18944	0.199107

Table D4 Mean Oscillatory Frequency Sweep Data for Emulsion 5

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	43.239	13.60125	0.31886	45.3315	4533.15	17.6821	0.081352	0.182665
0.015849	60.41385	18.3754	0.319788	63.4772	4005.135	17.5413	0.115345	0.179766
0.025119	73.923	19.3771	0.263507	76.5213	3046.37	14.72245	0.147084	0.192144
0.039811	85.45965	16.9864	0.197189	87.20665	2190.535	11.13546	0.1698	0.194907
0.063096	95.7418	19.20105	0.196865	97.7253	1548.845	11.11913	0.191645	0.196469
0.1	102.4711	20.2394	0.19361	104.5089	1045.089	10.94495	0.210031	0.200923
0.15849	110.1012	20.99565	0.188077	112.1039	707.328	10.64791	0.224479	0.200223
0.251189	116.3626	21.28925	0.180152	118.313	471.013	10.20901	0.237336	0.200575
0.398107	123.062	20.36065	0.159737	124.813	313.515	9.063865	0.249473	0.199854
0.630957	128.6835	19.75265	0.149823	130.2215	206.387	8.516615	0.259351	0.199269
1	136.4305	18.02535	0.128409	137.644	137.644	7.31414	0.273547	0.198775
1.5849	140.0625	20.4442	0.138382	141.6775	89.39245	7.863575	0.282568	0.199345
2.51189	147.347	20.12505	0.134105	148.727	59.2092	7.636735	0.296087	0.199137
3.98105	152.8665	21.78785	0.137426	154.466	38.80035	7.81912	0.309106	0.200106
6.30957	159.3995	22.75035	0.138532	161.051	25.5249	7.883345	0.321946	0.199902

10.0001	167.842	22.79345	0.131467	169.4215	16.9421	7.485895	0.339348	0.20018
15.849	178.649	24.20065	0.131066	180.3225	11.37754	7.463285	0.359457	0.199375
25.1188	195.173	25.706	0.127639	196.901	7.8388	7.27057	0.395104	0.200589
39.8105	228.945	27.459	0.116228	230.6355	5.79333	6.62668	0.461029	0.199869
63.0957	301.397	29.2409	0.09426	302.8635	4.800055	5.382915	0.604326	0.199557
100	480.1385	32.1102	0.065205	481.267	4.81267	3.72984	0.958971	0.199336

Table D5 Mean Oscillatory Frequency Sweep Data for Emulsion 6

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	120.385	29.1092	0.243144	123.8585	12385.85	13.665	0.229757	0.185256
0.015849	139.822	36.70595	0.27719	144.7995	9136.235	15.4377	0.293586	0.205463
0.025119	162.91	39.92745	0.245346	167.7315	6677.505	13.78495	0.330678	0.197088
0.039811	185.0865	39.3688	0.21709	189.273	4754.32	12.2421	0.373087	0.197478
0.063096	198.3635	43.4706	0.220219	203.074	3218.505	12.41895	0.403308	0.198688
0.1	212.347	45.45135	0.21466	217.1575	2171.575	12.11515	0.433081	0.199614
0.15849	226.1145	45.3374	0.198579	230.6275	1455.16	11.23025	0.46157	0.199959
0.251189	240.3135	45.21485	0.187371	244.532	973.502	10.6123	0.488314	0.199678
0.398107	255.1295	43.4558	0.172007	258.814	650.1115	9.75894	0.514685	0.198977
0.630957	267.3125	47.6406	0.179046	271.5275	430.342	10.15084	0.54369	0.200308
1	282.045	48.3849	0.175661	286.2285	286.2285	9.958365	0.57329	0.20045
1.5849	297.806	47.57715	0.159167	301.5845	190.2865	9.04363	0.6035	0.200024
2.51189	311.549	53.2941	0.170898	316.0745	125.831	9.698045	0.632364	0.200088
3.98105	326.121	58.85485	0.180886	331.39	83.2418	10.2531	0.664694	0.200525
6.30957	344.522	58.54145	0.169738	349.4605	55.38575	9.633415	0.69842	0.199834
10.0001	362.996	61.9034	0.170365	368.237	36.82345	9.668335	0.737016	0.200143
15.849	385.121	65.9138	0.171134	390.7205	24.65265	9.711195	0.781328	0.19991
25.1188	414.91	69.9848	0.168516	420.7715	16.75125	9.565355	0.840117	0.199665
39.8105	461.994	75.11335	0.162013	468.063	11.75728	9.202555	0.936016	0.199969

63.0957	552.053	81.57095	0.146851	558.059	8.84466	8.35381	1.114465	0.199705
100	744.1535	89.06665	0.118709	749.501	7.49501	6.76917	1.49333	0.199241

Table D6 Mean Oscillatory Frequency Sweep Data for Emulsion 7

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	130.5925	31.8681	0.245	134.426	13442.6	13.7659	0.256938	0.190711
0.015849	152.22	33.39635	0.218386	155.8435	9833.025	12.3187	0.308929	0.197797
0.025119	167.2465	36.20505	0.212873	171.167	6814.29	12.01045	0.339777	0.198315
0.039811	181.902	35.7474	0.193713	185.411	4657.31	10.95955	0.367701	0.198297
0.063096	193.4675	36.54355	0.186466	196.9125	3120.85	10.5598	0.392032	0.199014
0.1	205.3945	36.36765	0.177679	208.591	2085.91	10.07495	0.415121	0.199098
0.15849	215.008	39.4092	0.183386	218.59	1379.205	10.39175	0.438765	0.200655
0.251189	226.319	40.3568	0.178871	229.8905	915.2085	10.1412	0.458904	0.199676
0.398107	237.8025	40.2441	0.169693	241.185	605.829	9.630825	0.482779	0.200148
0.630957	249.4905	39.5468	0.161009	252.6325	400.395	9.144575	0.505355	0.2
1	261.5115	41.4332	0.15965	264.7805	264.7805	9.070235	0.52986	0.200154
1.5849	273.3415	44.15865	0.160994	276.8875	174.704	9.14566	0.554023	0.200065
2.51189	286.745	45.28865	0.15589	290.3225	115.5793	8.85908	0.580791	0.20002
3.98105	299.9025	46.12215	0.153434	303.429	76.21825	8.723045	0.607091	0.200068
6.30957	314.6185	48.49525	0.154017	318.334	50.4525	8.755735	0.635417	0.199597

10.0001	329.3355	51.8458	0.15681	333.394	33.3392	8.911825	0.666823	0.199982
15.849	349.2645	53.5047	0.152411	353.343	22.2943	8.665595	0.706525	0.199933
25.1188	375.158	57.1961	0.151567	379.499	15.10815	8.618275	0.759868	0.200256
39.8105	418.455	61.5654	0.146133	422.969	10.62454	8.31356	0.84623	0.200077
63.0957	503.6445	66.685	0.131287	508.059	8.05219	7.478805	1.015996	0.19997
100	692.501	73.14665	0.104625	696.3925	6.96392	5.97215	1.3922	0.199953

Table D7 Mean Oscillatory Frequency Sweep Data for Emulsion 8

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	118.3365	38.4181	0.325094	124.418	12441.8	18.00865	0.227666	0.182972
0.015849	163.331	44.1779	0.268609	169.2135	10676.66	15.03275	0.321462	0.190305
0.025119	187.0605	48.55855	0.259396	193.2605	7693.835	14.5418	0.382509	0.197865
0.039811	207.576	48.0728	0.231802	213.07	5352.08	13.05075	0.422828	0.198413
0.063096	222.9445	48.6815	0.217625	228.1995	3616.72	12.2773	0.454993	0.199284
0.1	236.385	48.6582	0.205395	241.3415	2413.415	11.6068	0.485387	0.200972
0.15849	252.0395	44.39835	0.176378	255.92	1614.745	10.00286	0.51065	0.199582
0.251189	265.0895	47.14265	0.178013	269.2485	1071.899	10.09365	0.538713	0.200043
0.398107	278.996	45.3978	0.161534	282.672	710.04	9.175505	0.564312	0.19959
0.630957	291.4275	47.9108	0.163818	295.341	468.084	9.30333	0.590163	0.199893
1	304.5885	47.74325	0.157886	308.314	308.314	8.971715	0.616539	0.200071
1.5849	317.863	48.8609	0.154375	321.599	202.915	8.77564	0.643557	0.200128

2.51189	331.5665	49.8543	0.152474	335.3175	133.492	8.667995	0.671138	0.200273
3.98105	346.758	50.1405	0.145555	350.3695	88.00935	8.281255	0.700794	0.200047
6.30957	361.212	52.6212	0.146381	365.0275	57.85295	8.327735	0.729012	0.199767
10.0001	378.419	54.31745	0.143866	382.298	38.22955	8.18667	0.763316	0.199741
15.849	398.191	57.12765	0.143082	402.269	25.3813	8.14263	0.804524	0.199963
25.1188	424.7065	61.30155	0.144152	429.1085	17.08315	8.202775	0.858546	0.200079
39.8105	469.9155	65.6148	0.139099	474.477	11.9184	7.91883	0.948117	0.199802
63.0957	556.6415	71.34545	0.127462	561.204	8.89448	7.263645	1.121373	0.199794
100	746.9335	78.25765	0.103985	751.0505	7.5105	5.936135	1.49542	0.199063

Table D8 Mean Oscillatory Frequency Sweep Data for Emulsion 9

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	93.44785	23.5798	0.252251	96.3776	9637.76	14.15735	0.179686	0.186412
0.015849	94.08815	31.4327	0.366792	99.8274	6298.68	19.8673	0.228263	0.237781
0.025119	122.9925	29.1946	0.236355	126.42	5032.87	13.296	0.248699	0.19665
0.039811	137.238	28.3794	0.208314	140.153	3520.48	11.7652	0.276179	0.197074
0.063096	147.3305	29.83285	0.201999	150.3225	2382.445	11.4198	0.299561	0.199256
0.1	159.331	30.0081	0.186873	162.144	1621.44	10.58336	0.32241	0.198923
0.15849	167.674	32.0991	0.190813	170.721	1077.176	10.80265	0.34004	0.199078
0.251189	176.746	32.14585	0.182626	179.6485	715.194	10.34925	0.36109	0.200991
0.398107	186.871	31.9008	0.171881	189.582	476.2085	9.751965	0.378324	0.19964
0.630957	196.649	32.82955	0.168826	199.3895	316.011	9.58076	0.39903	0.200078
1	205.534	33.0096	0.158181	208.2065	208.2065	8.98521	0.416716	0.2001
1.5849	215.511	34.4116	0.158737	218.2465	137.704	9.019215	0.436247	0.19982
2.51189	225.8885	33.0519	0.145902	228.295	90.88535	8.300895	0.456716	0.199904
3.98105	235.9375	36.2181	0.153961	238.7025	59.95975	8.7525	0.478638	0.200497
6.30957	247.538	37.15055	0.150277	250.31	39.6715	8.54626	0.500462	0.199941
10.0001	259.528	38.75335	0.14885	262.4075	26.24055	8.46617	0.524404	0.199853
15.849	274.631	40.6164	0.147566	277.619	17.51645	8.39425	0.5552	0.199963
25.1188	296.8825	42.99745	0.144427	299.9815	11.9425	8.218155	0.600038	0.200038
39.8105	336.007	45.93895	0.136286	339.135	8.518735	7.760685	0.678054	0.199952

63.0957	415.666	49.5636	0.118699	418.616	6.634625	6.76903	0.833947	0.199196
100	599.668	53.9948	0.089609	602.108	6.021075	5.120285	1.208955	0.200837

Table D9 Mean Oscillatory Frequency Sweep Data for Emulsion 10

Angular frequency	Storage modulus	Loss modulus	Tan(delta)	Complex modulus	Complex viscosity	Phase angle	Oscillation stress	Oscillation strain
rad/s	Pa	Pa		Pa	Pa.s	°	Pa	%
0.01	153.439	42.5543	0.277731	159.232	15923.2	15.5214	0.298329	0.187267
0.015849	189.2575	44.4658	0.23401	194.424	12267.3	13.169	0.377783	0.194157
0.025119	211.4305	52.73695	0.251273	217.9475	8676.65	14.0997	0.43222	0.198338
0.039811	230.336	55.32425	0.241628	236.917	5951.085	13.58035	0.471284	0.198946
0.063096	250.5925	53.83985	0.214605	256.312	4062.275	12.11215	0.511776	0.199654
0.1	269.3495	52.62205	0.194279	274.4765	2744.765	10.99155	0.547454	0.199407
0.15849	285.2485	56.13945	0.196923	290.7215	1834.325	11.14025	0.581346	0.19996
0.251189	300.7675	59.8504	0.200047	306.693	1220.97	11.31035	0.613978	0.20022
0.398107	317.7145	61.16815	0.192501	323.549	812.719	10.8962	0.647707	0.200145
0.630957	338.0925	53.20015	0.157746	342.258	542.442	8.96399	0.681366	0.19905
1	354.2765	57.9092	0.164083	358.9935	358.993	9.317435	0.714714	0.1991
1.5849	371.516	62.56335	0.168309	376.747	237.711	9.55382	0.752537	0.199714
2.51189	388.033	70.67865	0.181968	394.419	157.021	10.3131	0.790442	0.200434
3.98105	409.7695	68.83735	0.168074	415.512	104.3723	9.540705	0.830853	0.199959
6.30957	430.5535	72.3154	0.168509	436.5995	69.19635	9.56431	0.86974	0.199221

10.0001	453.939	74.46115	0.164027	460.0055	46.00025	9.315085	0.920705	0.20017
15.849	479.1245	81.63725	0.170407	486.0295	30.6662	9.670685	0.971993	0.199968
25.1188	513.856	86.4952	0.168456	521.0855	20.74485	9.562005	1.042278	0.200029
39.8105	566.874	92.96215	0.164059	574.4465	14.4295	9.31687	1.14877	0.199973
63.0957	663.108	101.1023	0.152485	670.771	10.631	8.66995	1.34182	0.200051
100	868.2195	111.118	0.127968	875.3015	8.75301	7.29234	1.74282	0.199083

Appendix E: Mean Oscillatory Temperature Sweep Data

Table E1 Mean Oscillatory Temperature Sweep Data for Emulsion 1

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N.m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
95.72765	18.3687	0.191786	6.28319	11.8279	19.11	5.13	11.14555	0.000168
69.26335	21.67485	0.313046	6.28319	8.574855	146.492	9.9745	18.0023	0.000165
70.9819	23.2193	0.327443	6.28319	8.85716	281.448	14.9545	18.7585	0.000165
76.02745	23.55645	0.309374	6.28319	9.471085	422.1525	19.953	17.7505	0.000166
84.6834	23.9461	0.283131	6.28319	10.43695	570.7505	24.9465	16.2837	0.000165
91.2052	24.06695	0.265245	6.28319	11.29863	728.116	29.958	15.27965	0.000166
98.8846	23.59975	0.245366	6.28319	12.23442	886.5885	34.93	14.1583	0.000166
104.5013	23.99705	0.237249	6.28319	12.79597	1051.53	39.9225	13.68985	0.000165

Table E2 Mean Oscillatory Temperature Sweep Data for Emulsion 2

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque (μN.m)	Step time (s)	Temperature ($^{\circ}$C)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
154.6235	30.0404	0.193974	6.28319	19.5381	21.8244	5.161	11.18015	0.00017
109.811	31.90215	0.279193	6.28319	13.84148	146.1835	9.97	15.95585	0.000166
105.759	32.025	0.291148	6.28319	13.32597	286.459	14.947	16.6258	0.000167
112.5728	31.3756	0.273076	6.28319	14.09093	436.742	19.969	15.6476	0.000166
119.2156	30.47225	0.255277	6.28319	14.87029	596.6575	24.933	14.6659	0.000166
120.028	29.0528	0.240151	6.28319	14.86233	760.146	29.8935	13.82685	0.000166
118.0483	27.80235	0.236912	6.28319	14.58222	937.1675	34.925	13.66095	0.000166
112.7241	28.60555	0.248708	6.28319	13.9909	1105.115	39.939	14.31765	0.000166

Table E3 Mean Oscillatory Temperature Sweep Data for Emulsion 4

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N.m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
731.679	168.241	0.229958	6.28319	93.47645	19.071	5.1645	12.99395	0.000168
553.5155	162.82	0.294824	6.28319	70.8274	139.7605	9.954	16.495	0.000166
481.9955	148.218	0.308961	6.28319	61.87885	281.2765	14.962	17.248	0.000166
449.625	136.6405	0.30527	6.28319	57.38735	430.2645	19.968	17.0601	0.000166
428.4835	133.1475	0.31131	6.28319	55.0074	572.32	24.9445	17.3818	0.000166
414.683	126.1985	0.30398	6.28319	53.0956	719.6855	29.933	16.9994	0.000166
397.6935	118.8975	0.298344	6.28319	50.6832	872.7925	34.934	16.70975	0.000166
396.433	116.4175	0.293037	6.28319	50.2596	1031.545	39.9295	16.429	0.000165

Table E4 Mean Oscillatory Temperature Sweep Data for Emulsion 5

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N}\cdot\text{m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
80.72395	12.87945	0.158571	6.28319	9.844035	13.806	5.1725	9.29824	0.000167
64.10055	14.83855	0.228837	6.28319	7.83822	133.53	9.981	13.38115	0.000167
63.36915	13.85335	0.216524	6.28319	7.757985	266.0365	14.9285	12.69915	0.000168
64.58655	13.47305	0.206321	6.28319	7.84327	415.3135	19.9285	12.11505	0.000166
65.46855	13.57435	0.206191	6.28319	7.94234	561.2	24.9295	12.10965	0.000166
65.45665	13.004	0.197367	6.28319	7.93459	699.0805	29.8935	11.6052	0.000167
66.40985	13.10015	0.196414	6.28319	7.99846	846.9215	34.914	11.5477	0.000166
68.49685	13.76115	0.199169	6.28319	8.27806	1001.439	39.912	11.69165	0.000166

Table E5 Mean Oscillatory Temperature Sweep Data for Emulsion 6

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N}\cdot\text{m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
309.848	77.2253	0.249286	6.28319	39.26975	21.879	5.128	14.10845	0.000167
230.284	78.92585	0.34272	6.28319	30.02605	149.5965	9.9795	19.11365	0.000168
212.0455	76.0819	0.36011	6.28319	27.35335	284.911	14.977	20.024	0.000166
215.2985	75.0719	0.350503	6.28319	27.6838	418.9235	19.9475	19.522	0.000165
225.402	72.88545	0.323615	6.28319	28.67225	562.2875	24.9485	18.12205	0.000165
227.964	67.82085	0.297473	6.28319	28.85135	713.366	29.9365	16.73845	0.000165
226.043	65.13695	0.287716	6.28319	28.5391	871.1525	34.9395	16.2209	0.000165
223.9325	64.4022	0.287434	6.28319	28.2824	1029.49	39.913	16.21085	0.000165

Table E6 Mean Oscillatory Temperature Sweep Data for Emulsion 7

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque (μN.m)	Step time (s)	Temperature ($^{\circ}$C)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
257.634	55.4422	0.213524	6.28319	32.55455	19.1256	5.1585	12.171	0.000168
193.708	59.91405	0.31688	6.28319	24.5759	143.809	9.991	17.79705	0.000165
184.056	60.14525	0.332899	6.28319	23.50195	278.78	14.93	18.64485	0.000166
190.84	58.9952	0.310674	6.28319	24.5084	429.3925	19.952	17.48055	0.000167
193.9425	57.7423	0.299906	6.28319	24.50765	568.8025	24.958	16.9053	0.000165
191.714	59.0585	0.307417	6.28319	24.30345	711.023	29.9045	17.30835	0.000165
191.842	55.25125	0.289143	6.28319	24.342	862.9945	34.923	16.3379	0.000166
192.743	50.66775	0.265293	6.28319	24.1061	1017.965	39.913	15.05145	0.000165

Table E7 Mean Oscillatory Temperature Sweep Data for Emulsion 8

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N}\cdot\text{m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
212.135	37.1567	0.1748	6.28319	26.4563	19.1802	5.1645	10.03293	0.000168
164.4265	41.15175	0.252008	6.28319	20.54995	139.932	9.96	14.35775	0.000166
155.828	39.4718	0.254824	6.28319	19.43745	277.0255	14.939	14.52215	0.000166
153.7355	37.4891	0.243879	6.28319	19.1918	423.1715	19.929	13.92755	0.000166
152.4115	36.1078	0.236511	6.28319	18.92455	583.2625	24.924	13.521	0.000166
147.8475	35.08585	0.237257	6.28319	18.383	737.305	29.9485	13.572	0.000166
143.443	34.52305	0.240563	6.28319	17.9161	893.9415	34.9375	13.761	0.000167
143.184	34.045	0.237814	6.28319	17.79625	1052.447	39.909	13.6102	0.000166

Table E8 Mean Oscillatory Temperature Sweep Data for Emulsion 9

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque (μN.m)	Step time (s)	Temperature ($^{\circ}$C)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
146.9985	27.6711	0.188287	6.28319	18.3759	19.11	5.1635	10.84595	0.000168
111.967	31.6418	0.284273	6.28319	14.0205	144.1595	9.97	16.2109	0.000166
111.547	31.23845	0.28057	6.28319	13.91925	287.0325	14.9415	16.01215	0.000165
112.6445	31.84895	0.282807	6.28319	14.17495	427.979	19.918	16.1355	0.000167
115.035	29.16465	0.253538	6.28319	14.2419	582.786	24.9305	14.53435	0.000165
112.289	29.05285	0.258763	6.28319	13.911	741.9685	29.951	14.82785	0.000165
110.1655	28.32335	0.257108	6.28319	13.70315	891.846	34.917	14.7445	0.000166
108.784	27.52745	0.253165	6.28319	13.44225	1048.22	39.9265	14.53085	0.000165

Table E9 Mean Oscillatory Temperature Sweep Data for Emulsion 10

Storage modulus (Pa)	Loss modulus (Pa)	Tan(delta)	Angular frequency (rad/s)	Oscillation torque ($\mu\text{N}\cdot\text{m}$)	Step time (s)	Temperature ($^{\circ}\text{C}$)	Raw phase ($^{\circ}$)	Oscillation displacement (rad)
506.664	114.1891	0.224869	6.28319	64.03885	16.4424	5.124	12.7365	0.000167
393.0515	115.3745	0.296524	6.28319	50.2569	146.43	9.9695	16.6208	0.000166
340.9825	110.0836	0.33177	6.28319	44.19945	286.5725	14.9735	18.47585	0.000168
334.962	105.8506	0.325867	6.28319	42.9591	428.1585	19.9555	18.1645	0.000166
342.8305	102.7911	0.305597	6.28319	43.47115	578.6285	24.952	17.1045	0.000165
342.9795	100.0228	0.29455	6.28319	43.80175	730.635	29.924	16.5223	0.000166
336.44	93.1108	0.278561	6.28319	42.5919	890.1685	34.921	15.6726	0.000166
324.6455	91.1713	0.28145	6.28319	41.217	1054.86	39.924	15.83595	0.000166

Appendix F: Mean Oscillatory Time Sweep Data

Table F1 Mean Oscillatory Time Sweep Data for Emulsion 1

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	$\mu\text{N.m}$	S	$^{\circ}\text{C}$	$^{\circ}$	rad
136.087	18.90565	0.138497	6.28319	16.61685	302.789	25.004	8.03484	0.000166
140.171	19.061	0.135736	6.28319	17.1096	600.8195	25.002	7.87257	0.000166
131.1915	19.45145	0.150658	6.28319	15.87525	907.696	24.9975	8.745225	0.000164
140.641	19.33105	0.137604	6.28319	17.18735	1203.15	24.9975	7.981575	0.000166
145.3515	19.202	0.131919	6.28319	17.72575	1500.98	25.0055	7.6501	0.000166
148.5665	19.3906	0.129922	6.28319	18.1485	1803.45	24.999	7.53187	0.000166
151.4185	20.3056	0.134236	6.28319	18.51645	2100.47	25.0025	7.77705	0.000166
154.3565	19.905	0.12872	6.28319	18.86745	2404.19	25.0015	7.45815	0.000166
156.919	20.1475	0.128209	6.28319	19.16795	2702.01	25.0045	7.42674	0.000166
159.3355	20.44385	0.128406	6.28319	19.4728	3002.65	24.9975	7.436365	0.000166
161.841	20.455	0.126233	6.28319	19.7791	3303.645	25.0005	7.30965	0.000166
164.132	20.92225	0.127317	6.28319	20.07565	3604.215	24.994	7.36992	0.000166

Table F2 Mean Oscillatory Time Sweep Data for Emulsion 2

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	S	°C	°	rad
179.743	27.77405	0.15472	6.28319	22.0873	302.8825	25.0015	8.919335	0.000166
185.0475	27.67525	0.149472	6.28319	22.72055	602.668	25.0005	8.61779	0.000166
189.441	28.23605	0.14904	6.28319	23.2785	901.0495	25	8.59056	0.000166
192.8885	29.9628	0.155482	6.28319	23.7712	1202.73	25.003	8.953855	0.000166
197.4125	28.7826	0.145743	6.28319	24.25	1503.935	24.998	8.398635	0.000166
200.731	29.40505	0.146421	6.28319	24.67245	1802.075	25.006	8.43534	0.000166
204.147	29.06485	0.142207	6.28319	25.0637	2103.265	25.001	8.19389	0.000166
207.349	29.2536	0.14106	6.28319	25.4742	2404.34	24.996	8.1275	0.000166
210.036	30.3275	0.144286	6.28319	25.80455	2703.035	25.0005	8.30928	0.000166
212.4885	31.30675	0.14752	6.28319	26.182	3004.05	24.999	8.491715	0.000166
215.459	30.77235	0.142688	6.28319	26.5315	3302.255	25.005	8.21593	0.000166
218.0195	31.38465	0.143874	6.28319	26.8287	3603.385	24.998	8.282275	0.000166

Table F3 Mean Oscillatory Time Sweep Data for Emulsion 4

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
524.5365	103.9266	0.198232	6.28319	65.5949	302.5565	25.0005	11.266	0.000166
540.477	104.9079	0.193814	6.28319	67.43025	600.8135	24.9975	11.01935	0.000166
553.5135	106.6408	0.192424	6.28319	69.14625	904.5845	24.9945	10.9411	0.000166
565.2565	107.585	0.190459	6.28319	70.6214	1206.05	25.004	10.83115	0.000166
575.908	108.913	0.189126	6.28319	71.94855	1501.19	25.006	10.7562	0.000166
585.8635	111.058	0.189747	6.28319	73.11925	1804.885	24.999	10.7899	0.000166
595.1565	111.826	0.18773	6.28319	74.2411	2102.465	25.001	10.67705	0.000166
604.095	112.86	0.186991	6.28319	75.42165	2402.67	24.9995	10.63545	0.000166
612.1865	115.181	0.187924	6.28319	76.4411	2703.875	24.9965	10.68655	0.000166
621.6645	113.757	0.182897	6.28319	77.40535	3004.205	25.0005	10.4065	0.000166
628.1455	118.008	0.188062	6.28319	78.5354	3304.485	24.9945	10.6932	0.000166
635.547	120.219	0.188897	6.28319	79.4248	3603.105	25.005	10.7389	0.000166

Table F4 Mean Oscillatory Time Sweep Data for Emulsion 5

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
94.46725	13.833	0.147515	6.28319	11.43165	303.795	25.0055	8.622635	0.000166
99.92225	13.4614	0.135361	6.28319	12.0922	603.9	25.0015	7.90885	0.000166
105.2946	14.5534	0.138227	6.28319	12.77835	902.922	24.9955	8.062725	0.000166
108.0955	14.7935	0.136983	6.28319	13.1413	1202.795	24.993	7.9866	0.000166
112.5055	14.9636	0.132934	6.28319	13.6819	1502.04	24.9975	7.74578	0.000166
114.328	15.50245	0.135727	6.28319	13.89895	1804.605	25.0045	7.90435	0.000166
119.1995	15.7938	0.132965	6.28319	14.49535	2104.635	25.0065	7.738165	0.000166
114.9066	15.92635	0.140667	6.28319	13.9338	2406.64	25.003	8.1913	0.000165
122.846	15.8654	0.129475	6.28319	14.92595	2701.47	25	7.53353	0.000166
125.8385	16.3626	0.130386	6.28319	15.3157	3003.75	25.0015	7.581695	0.000166
129.222	16.3806	0.126908	6.28319	15.7116	3303.655	25.0005	7.377625	0.000166
132.2035	17.09645	0.129369	6.28319	16.11955	3601.775	25.0005	7.515525	0.000166

Table F5 Mean Oscillatory Time Sweep Data for Emulsion 6

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
215.719	43.35805	0.208971	6.28319	26.9026	303.064	25.0025	11.94405	0.000167
221.829	44.5239	0.208017	6.28319	27.6474	604.854	24.9965	11.8879	0.000166
228.489	44.28775	0.199977	6.28319	28.43895	901.707	24.996	11.43775	0.000166
234.2915	45.10725	0.197446	6.28319	29.21015	1202.92	24.9935	11.29425	0.000167
240.464	46.6535	0.19946	6.28319	29.83795	1503.845	24.9945	11.40115	0.000166
247.853	45.63825	0.190062	6.28319	30.686	1802.995	24.9995	10.87167	0.000166
253.8565	46.53625	0.188907	6.28319	31.51885	2105.22	25	10.80385	0.000166
258.959	48.74165	0.192	6.28319	32.25305	2403.935	25.0025	10.97604	0.000167
265.4685	48.6914	0.188436	6.28319	32.9752	2704.855	24.9985	10.7714	0.000166
271.702	47.94095	0.180226	6.28319	33.64345	3002.48	25.0045	10.31165	0.000166
276.256	50.0916	0.185804	6.28319	34.3432	3304.415	25.0015	10.61992	0.000166
281.744	51.24835	0.185178	6.28319	34.90155	3605.8	25.0035	10.58457	0.000166

Table F6 Mean Oscillatory Time Sweep Data for Emulsion 7

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
208.3915	34.84025	0.166992	6.28319	25.7275	302.789	24.9985	9.5946	0.000166
215.157	36.0397	0.167427	6.28319	26.54795	602.816	24.9995	9.61607	0.000166
221.404	36.2497	0.163629	6.28319	27.35255	903.4835	24.9945	9.398765	0.000166
227.402	36.9748	0.162468	6.28319	28.0474	1201.575	25.0035	9.330455	0.000166
233.007	37.69035	0.161493	6.28319	28.7774	1502.81	24.995	9.272665	0.000166
238.4	39.19285	0.164319	6.28319	29.4237	1803.95	25.005	9.43022	0.000166
244.399	39.01905	0.15937	6.28319	30.2005	2108.355	24.9995	9.14841	0.000166
249.3965	40.57035	0.162589	6.28319	30.89445	2402.835	25.0025	9.32851	0.000167
255.336	40.50435	0.158149	6.28319	31.50065	2703.97	24.999	9.075355	0.000166
259.87	43.0717	0.165325	6.28319	32.1998	3001.595	24.993	9.478525	0.000166
265.7625	43.33305	0.162386	6.28319	32.86705	3302.825	24.9965	9.31065	0.000166
272.3355	42.5654	0.155562	6.28319	33.61615	3603.35	25.005	8.923795	0.000166

Table F7 Mean Oscillatory Time Sweep Data for Emulsion 8

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
191	29.62405	0.156645	6.28319	23.488	301.72	25.004	9.021415	0.000166
196.7555	30.1873	0.155003	6.28319	24.1753	602.9955	25.005	8.92443	0.000166
200.979	31.02535	0.155741	6.28319	24.7164	903.0075	25.0045	8.963605	0.000166
206.2855	30.8838	0.151018	6.28319	25.40325	1200.6	25.0045	8.693015	0.000166
211.028	31.6176	0.150807	6.28319	25.94545	1503.295	24.995	8.67894	0.000166
214.0905	32.1724	0.151574	6.28319	26.4098	1802.49	25.0015	8.72025	0.000166
218.705	33.10495	0.151834	6.28319	26.9831	2100.85	25.005	8.73379	0.000166
223.002	32.93035	0.148832	6.28319	27.4925	2404.18	24.9975	8.560405	0.000166
226.2535	34.0179	0.150833	6.28319	27.93945	2701.47	25.003	8.673565	0.000166
230.639	34.3307	0.149183	6.28319	28.43835	3003.065	25.002	8.5783	0.000166
235.1805	33.63365	0.143272	6.28319	28.90745	3304.105	25.001	8.24138	0.000166
238.7385	34.5046	0.144743	6.28319	29.41655	3601.95	25.002	8.323495	0.000166

Table F8 Mean Oscillatory Time Sweep Data for Emulsion 9

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
153.939	26.1416	0.168994	6.28319	18.8962	302.2195	25.004	9.74579	0.000166
162.674	27.9101	0.170787	6.28319	20.0026	600.8585	24.9985	9.84119	0.000166
171.897	28.6108	0.165242	6.28319	21.18075	907.7735	24.998	9.51928	0.000166
180.649	29.761	0.163508	6.28319	22.21795	1203.645	25.002	9.41554	0.000166
188.383	30.3387	0.160389	6.28319	23.22375	1500.815	25.002	9.235575	0.000166
196.4755	30.7748	0.155307	6.28319	24.1669	1803.965	24.995	8.942085	0.000166
203.1235	33.2602	0.162534	6.28319	25.02975	2102.185	25.007	9.3479	0.000166
210.6765	34.0613	0.160234	6.28319	25.9934	2403.29	25.0005	9.21382	0.000166
217.3925	35.42135	0.161101	6.28319	26.81205	2702.915	25.0075	9.25911	0.000166
224.288	36.8879	0.161861	6.28319	27.6473	3003.505	25.0045	9.297545	0.000166
231.3925	38.0181	0.162556	6.28319	28.58505	3301.13	25.001	9.335635	0.000166
236.4225	38.53695	0.160871	6.28319	29.2059	3603.27	25.005	9.237665	0.000166

Table F9 Mean Oscillatory Time Sweep Data for Emulsion 10

Storage modulus	Loss modulus	Tan(delta)	Angular frequency	Oscillation torque	Step time	Temperature	Raw phase	Oscillation displacement
Pa	Pa		rad/s	μN.m	s	°C	°	rad
361.23	64.2787	0.178128	6.28319	44.8547	302.313	24.9975	10.1704	0.000166
371.63	66.34735	0.178207	6.28319	46.18195	603.51	24.998	10.1725	0.000166
380.862	66.7022	0.174857	6.28319	47.3625	902.9605	25.0005	9.98356	0.000166
388.5885	68.05385	0.175338	6.28319	48.33395	1201.145	24.996	10.00943	0.000166
396.7595	67.447	0.169832	6.28319	49.22495	1501.81	25.0035	9.699725	0.000166
403.5	68.4287	0.169465	6.28319	50.14965	1805.135	25.0025	9.678215	0.000166
409.842	69.1682	0.168716	6.28319	50.86045	2103.635	25	9.635385	0.000166
414.132	73.42665	0.17734	6.28319	51.5847	2403.46	25.0055	10.11735	0.000166
419.5165	74.6707	0.178029	6.28319	52.3522	2704.195	25.0045	10.155	0.000167
427.0995	71.758	0.167867	6.28319	53.0323	3002.09	25.0035	9.58533	0.000166
430.7395	75.60895	0.175411	6.28319	53.74905	3302.715	25.0015	10.00711	0.000167
437.5735	74.09145	0.169311	6.28319	54.3	3602.485	24.997	9.664955	0.000166