



# Assessment of soy soluble polysaccharide, gum arabic and OSA-Starch as emulsifiers for mayonnaise-like emulsions



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## ABSTRACT

Hydrocolloid emulsifiers, soy soluble polysaccharide (SSPS), gum arabic (GA), and octenyl succinate starch (OSA-S), were investigated for their ability to produce oil-in-water (O/W) mayonnaise-like emulsions. Xanthan gum (XG) was used as a stabilizer and/or thickener. Oil content above 60%wt. could not be completely emulsified by all three types of emulsifiers. Emulsion separation was observed immediately after preparation. Long term emulsion stability depended on the amount of dispersed phase with higher dispersed phase contents conferring more stability due to a strong network of droplets formed in the system. The formation of Pickering emulsions was confirmed in OSA-S stabilized emulsions. All emulsion systems showed pseudoplastic behavior similar to typical mayonnaise, which increased with an increase in the dispersed phase volume. It was concluded that it is possible to employ hydrocolloid emulsifiers to produce mayonnaise.

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## 1. Introduction

Mayonnaise is a semi-solid O/W emulsion formed of vegetable oil, acidifying ingredients (vinegar) and egg yolk (Nikzade, Mazaheri Tehrani, & Saadatmand-Tarzjan, 2012; Langton, Jordanson, Altskär, Sørensen, & Hermansson, 1999). Salt, flavors, sweetening and food seasonings may also be added to mayonnaise. Mayonnaise is probably one of the oldest and most widely used sauces in the world today (Depree & Savage, 2001). Despite containing 70–80% fat, typical traditional mayonnaise is an O/W emulsion. Careful mixing of the ingredients and the addition of minor constituents help to maintain a closely packed foam of oil droplets.

Of late, the food industry has been under pressure from the growing number of health oriented consumers to reduce the amount of fat, sugar, cholesterol, salt and certain additives in the diet (Liu, Xu, & Guo, 2007). Among mayonnaise ingredients, egg yolk is most critical for the stability (Harrison & Cunningham, 1985) and organoleptic properties imparted on the product. Egg yolk has

outstanding qualities both for forming the emulsion and for the way that egg yolk emulsions flocculate to give the correct texture (Depree & Savage, 2001). Nevertheless, one main problem with egg yolk is high cholesterol content. Different attempts have been carried out to develop low cholesterol sauces with similar characteristic to real mayonnaise (Laca, Sáenz, Paredes, & Díaz, 2010). In this study, hydrocolloid emulsifiers, GA, SSPS, and OSA-S in combination with xanthan gum as a stabilizer, were assessed for their potential to produce stable mayonnaise-like O/W emulsions.

OSA-S is derived from hydrophobic modification of starch molecules with octenyl succinic anhydride (OSA). The hydrophobic OSA incorporated into the hydrophilic structure of native starch converts starch into an amphiphilic substance and give it surface active properties (Nilsson & Bergenstahl, 2007). The short octenyl succinate side chains bring OSA-S molecules to the oil/water interface, and the large amylopectin backbone protects the droplets against flocculation via steric stabilization (Bhosale & Singhal, 2006; Dickinson, 2009). OSA-S can be used as both an emulsifier and a thickening agent in O/W emulsions. Formation of a network with other polymers in aqueous solution through hydrophobic interactions causes an increase in the viscosity of the system and can therefore stabilize droplet particles (Krstonosic, Dokic, Nikolic, & Milanovic, 2015). The advantages of using OSA-S in culinary products like low fat spreads are that OSA-S is cholesterol free

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unlike egg yolk, may act as a combination of emulsifier and stabilizer (Tesch, Gerhards, & Schubert, 2002), and is microbial safe (Bortnowska & Tokarczyk, 2009).

GA, the natural exudate from *Acacia senegal*, is a high molecular weight polysaccharide consisting of branched arabinogalactan heteropolymers (Dickinson, 2003). The structure of GA contains proteinaceous material (ca. 2%wt.) covalently attached to the polysaccharide moiety (Akiyama, Eda, & Kato, 1984). This protein component makes GA surface active and it is mainly associated with a high molecular weight fraction representing less than 30% of the total gum (Vandeveldt & Fenyo, 1985). It has been shown that the protein containing fraction adsorbs strongly at the oil/water interface (Randall, Phillips, & Williams, 1988). SSPS are a family of pectin-like acidic biopolymers extracted from the residual carbohydrate byproduct (*okara* in Japanese) of soy protein isolate (SPI) production. They are composed of a main rhamnogalacturonan backbone branched with  $\beta$ -1,4-galactan and  $\alpha$ -1,3 or  $\alpha$ -1,5-arabinan chains, and homogalacturonan covalently bound to a ~50 kDa protein moiety that is essential for surface activity (Nakamura, Yoshida, Maeda, & Corredig, 2006, 2004). SSPS have high water solubility, pH stability, low bulk viscosity, and are able to form strong interfacial films of 17–30 nm thick capable of stabilizing emulsions via steric repulsion (Nakamura et al., 2004; 2006).

To achieve mayonnaise with appropriate emulsion properties and high stability, several investigations have been conducted mostly by using proteins with various emulsifiers and gums such as xanthan and guar gums (Bortnowska & Tokarczyk, 2009; Lorenzo, Zaritzky, & Califano, 2008). In the present study, hydrocolloid emulsifiers in combination with XG were used. Ma and Barbarosa-Cánovas (1995) and Mandala, Savvas, and Kostaropoulos (2004) reported that the addition of XG to O/W emulsions improves the textural properties. The ability of xanthan gum to thicken and stabilize emulsion systems is attributed to a weak gel-like structure in solution formed by XG molecules in the emulsion continuous phase which prevents the oil droplets to cream since the gravitational lift on the droplets is less than the yield stress of the xanthan weak gel (Bortnowska & Tokarczyk, 2009).

The aim of this study was to assess the possibility of employing hydrocolloid emulsifiers as sole emulsifiers in combination with XG as a stabilizer and/or thickener to formulate mayonnaise-like O/W emulsions. Moreover, different rheological models were tested to find an appropriate model that can be used to correlate the shear rate and shear stress data.

## 2. Experimental

### 2.1. Materials

SSPS was prepared using the method of Nakamura et al., (2004). SSPS was extracted from *okara* (soy bean residue after extraction of oil and protein) using hot water by heating at 120 °C, pH 3.0 for 2 h. Insoluble materials were then removed by centrifugation and the extract was desalted by electric dialysis before being spray dried. The sugar composition (mol %) of SSPS is rhamnose - 4.3; fucose - 1.5; arabinose - 15.3; galactose - 48.3; xylose - 1.5; glucose - 1.6; and galacturonic acid - 27.5 while protein (dry %) content is 8.2 (Nakamura et al., 2004). Xanthan gum (XG) was purchased from Sigma (Sigma–Aldrich, St. Louis, MO). Commercial food grade Gum Arabic (GA) was purchased from Nacalai Tesque, Inc (Kyoto, Japan). Food grade modified waxy corn starch, octenyl succinic anhydride starch (OSA-S), was purchased from Cargill Japan, Tokyo. Vegetable oil (consisting of soybean oil and rapeseed oil) produced by Nisshin Oillio Pvt. Ltd. was purchased from conventional supermarket. Sodium chloride and sucrose were purchased from Nacalai Tesque, Inc (Kyoto, Japan). Acetic acid was purchased from Wako Pure

Chemical Industries, Ltd. (Osaka, Japan).

### 2.2. Preparation of emulsions

In this study, 70 g of each mayonnaise sample was prepared. The recipe contained the following ingredients in percentage weight: emulsifier (SSPS; GA; or OSA-S) 10, vegetable oil 40, 50, and 60, 10% (w/v) acetic acid 3.5, sodium chloride 1.0, sucrose 0.5, xanthan gum (XG) stabilizer 0.3 and the remaining percentage was water. Out of the remaining percentage of water, a given amount was used to dissolve XG polysaccharide. After vigorous stirring at room temperature, XG dispersions were refrigerated overnight to allow for complete hydration. The remaining amount of water was used to dissolve SSPS, GA, or OSA-S at room temperature. The emulsifier solution, XG dispersion, salt, sugar and acetic acid were rigorously mixed until a homogenous paste was formed. Oil was then carefully added drop-wise into the aqueous phase while mixing at 300 rpm using a paddle (Eyela Mazela Z, Japan). After all the oil had been completely mixed, the emulsions were homogenized at 15 000 rpm for 1 min using a rotor-stator homogenizer Ultra-Turrax T25 (Janke & Kunnell, IKA Labortechnik, Germany).

### 2.3. Droplet size distribution analysis

The Emulsion Droplet Size (EDS) ( $d_{3,2}$ ) and the Droplet Size Distribution (DSD) were determined using a laser diffraction particle size analyzer SALD-3000 (Shimadzu Co., Ltd, Japan). Data was analyzed using an installed software Wing SALD-3000J to determine the EDS and the DSD patterns. Samples were measured approximately 2 h after preparation.

### 2.4. Microstructure observation

Microscopic images were taken using normal light and polarized light on microscope BX51 (Olympus, Japan). An aliquot of undiluted emulsion sample was put onto the slide and covered with a cover slip ensuring that no air was trapped in-between the cover and the slide. After 5–10 min of equilibration, examination was performed at suitable magnification.

### 2.5. Stability determination

Ten grams ( $F_0$ ) of freshly prepared emulsion samples were weighed into centrifuge glass tubes and centrifuged at 201.1 g for 30 min at room temperature. The weight of the precipitated fraction ( $F_1$ ) was measured and stability calculated as percentage (%) =  $(F_1/F_0) \times 100$ . In order to determine heat stability, samples weighed into centrifuge glass tubes were heated at 80 °C for 30 min. The samples were then centrifuged at 201.1 g for 30 min and stability was calculated using the formula specified above.

### 2.6. Viscosity measurement

The O/W emulsion viscosity was determined by means of viscometers TV-20 or TV-30 (Toki Sangyo Co. Ltd, Japan). The angle and the gap between the cone and plate for both equipments were 1° 34' and 12.5  $\mu$ m, respectively. After equilibrating the samples to 25 °C, shear stress and viscosity readings were collected at each shear rate point after subjecting the sample to shear for 60 s. The shear rate used ranged within 3.83 s<sup>-1</sup> to 383 s<sup>-1</sup>. Experimental flow curves of shear stress against shear rate were compared to common rheological models, such as the Power Law model (Eq. (1)), Bingham Plastic model (Eq. (2)), Herschel-Bulkley model (Eq. (3)), and the Casson model (Eq. 4) (Bhattacharya & Bhattacharya, 1996; Sopade et al., 2008; Nehdi & Rahman, 2004; Khalili

Garakani et al., 2011).

$$\tau = K_P \cdot \dot{\gamma}^{nP} \quad (1)$$

$$\tau = \tau_{oB} + \mu_B \cdot \dot{\gamma} \quad (2)$$

$$\tau = \tau_{oHB} + K_{HB} \cdot \dot{\gamma}^{nHB} \quad (3)$$

$$\tau^{0.5} = \tau_{oC}^{0.5} + \mu_{\infty C} \cdot \dot{\gamma}^{0.5} \quad (4)$$

In these models,  $\tau$  (Pa) is the shear stress,  $\dot{\gamma}$  ( $s^{-1}$ ) is the shear rate,  $\tau_o$  (Pa) is the yield stress,  $\mu$  (Pa s) is the limiting viscosity,  $\mu_{\infty}$  (Pa s) is the viscosity at infinite shear rate,  $K$  (Pa  $s^n$ ) is the consistency index, and  $n$  is the dimensionless flow behavior index. The subscripts P, B, HB, and C represent the Power Law, Bingham Plastic, Herschel-Bulkley, and the Casson models respectively. The standard error for the various rheological models used was calculated using Eq. (5) (Nehdi & Rahman, 2004). Standard error is a scale of the relative level of accuracy of the different rheological models.

$$S.E. = 1000 \times \left[ \sum (X_m - X_c)^2 / (n - 2) \right]^{1/2} / \text{Range} \quad (5)$$

In this equation,  $X_m$ ,  $X_c$  and  $n$  are the measured values, calculated values and number of data points, respectively. Range is the maximum minus minimum of the measured values.

### 3. Results and discussions

#### 3.1. Droplet size distribution

Typical mayonnaise consists of oil content as high as 80%. The amount of oil that can be emulsified by SSPS, GA, and OSA-S hydrocolloid emulsifiers was investigated. A maximum oil content of 60%wt. could be emulsified by all three emulsifiers producing a stable emulsion with measurable parameters. In agreement to our results, Bortnowska and Tokarczyk (2009) also reported that modified starch was a capable emulsifier with the potential to replace egg yolk in manufacturing mayonnaise-like dressing. They found that it was possible to emulsify similar amount of oil as in mayonnaise produced by dried egg yolk. With all the three emulsifiers tested in this study, oil content above 60%wt. could not be fully emulsified. Non emulsified oil could be observed within the emulsions and sudden oiling off occurred after leaving the emulsion to stand for a short time. Fig. 1 shows a picture of emulsions when preparation of an O/W mayonnaise-like emulsion containing 70%wt. of oil was attempted.

The DSD of all prepared emulsions as seen in Fig. 2 exhibited clear bi-modal distribution. In the case of SSPS and GA stabilized emulsions, the maximum volume for emulsions containing 60%wt. oil was high compared to emulsions with lower oil content. This signifies an increase in the volume of emulsion droplets produced. However, EDS ( $d_{3,2}$ ) became bigger especially in SSPS stabilized emulsions. On the other hand, emulsions stabilized by OSA-S produced similar DSD regardless of the oil concentration. Un-adsorbed starch granules appear as the small peak in the DSD patterns in Fig. 2c, hence the bi-modal DSD observed for OSA-S emulsions. The particle sizes of OSA-S suspension was measured and it was confirmed that the peak at around 10  $\mu\text{m}$  originated from the starch particles (data not shown). Therefore, the EDS shown in Fig. 2c was calculated excluding the part arising from the starch granules. There was some floating oil observed on top of the prepared emulsion samples when 60%wt. oil content was emulsified. However, the emulsions did not phase separate within a storage period of up to two months.

The DSD of stored emulsions measured after 30 days were the same as in fresh emulsion samples for all the three types of emulsifiers (results not shown). This confirms the long term stability of these concentrated emulsions. The micrographs in Fig. 3 confirm the structure of O/W mayonnaise-like emulsions. Emulsion droplets were highly packed in all systems. In OSA-S emulsion system, starch granules are arranged along the oil/water interface creating a mechanical barrier against each oil droplet.

In order to confirm the adsorption of starch granules on the oil/water interface, OSA-S stabilized emulsions were diluted a hundred times by water to separate the droplets. Fig. 4 confirms the adsorption of starch granules as they can be clearly visualized under light microscopy. Polarized light was further used where birefringence confirmed the presence of starch crystals at the oil/water interface. The formation of the so-called Pickering emulsions was therefore confirmed in O/W mayonnaise-like emulsions.

#### 3.2. Accelerated stability

High oil concentration emulsions similar to the ones produced in this study are normally very stable to gravitational destabilization due to the network formed among the densely packed emulsion droplets (Al-Sayed, Rasmy, Rizk, & Yousef, 2012). In order to assess the stability of emulsions without having to wait for long periods of time, accelerated stability techniques were used. In this case centrifugation of fresh and heat treated emulsions was performed. When accelerated stability of fresh emulsions was assessed (Fig. 5a), the extent of phase separation decreased with an increase in the oil content for SSPS and GA stabilized emulsions. Therefore, emulsion stability increased with increasing oil content. The higher extent of syneresis observed in the lower oil content SSPS or GA stabilized emulsions was due to the weak emulsion structure with low viscosity. Emulsion droplets had some extent of free mobility space enhancing the chances of syneresis (Nor Hayati et al., 2009). Higher oil contents produced emulsions with highly packed droplets forming a strong network such that syneresis could not occur easily. At all the tested oil contents, GA stabilized emulsions phase separated to a slightly greater extent when compared to SSPS stabilized emulsions. Emulsion destabilization is facilitated by the presence of large droplet sizes such that SSPS stabilized emulsions were expected to separate to a greater extent when compared to the GA stabilized emulsions (for example, as shown in Fig. 2, EDS at 60% oil contents for SSPS stabilized emulsions were 20  $\mu\text{m}$  compared to 6  $\mu\text{m}$  for GA stabilized emulsions). It is therefore presumed that differences in viscosity led to the slight variations in syneresis extent. Moreover, SSPS might have formed a better network when used in combination with XG in the continuous phase compared to the network produced in GA emulsion system. On the other hand, OSA-S stabilized emulsions showed an increase in the amount of starch granule sediment and oiling off with increasing oil concentration. OSA-S stabilized emulsions were weak against centrifugal forces.

After heat treatment (Fig. 5b), no big change was observed except for a slight reduction in syneresis for both SSPS and GA stabilized emulsions. This was presumed to have occurred due to changes in structure of XG after heating. In aqueous solutions, XG exhibits a secondary double helix structure which unwinds upon heating and that complete unwinding can only be obtained after prolonged heating at high temperature (Desplanques, Renou, Grisel, & Malhiac, 2012). In the ordered conformation, the side chains are folded in and associated with the backbone, while in the disordered structure, the side chains are not associated and project away from the backbone (Pelletier, Viebke, Meadows, & Williams, 2001). It is thought that during emulsion heating, the side chains of XG partially unfolded and further built a strong network of

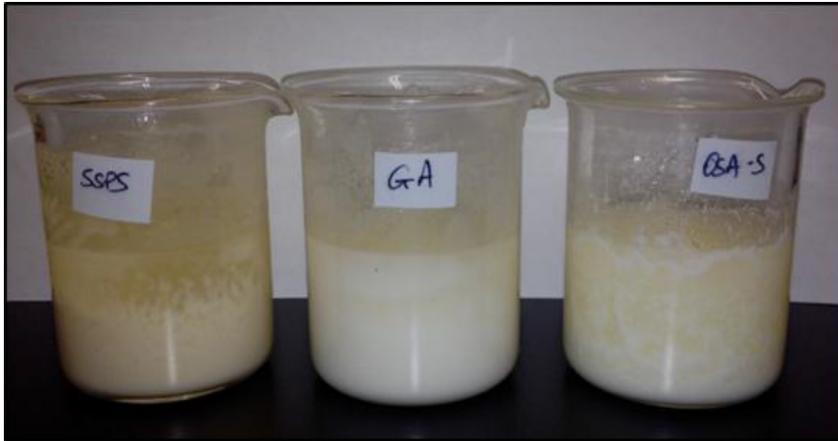


Fig. 1. Non emulsified oil observed 5 min after preparation of O/W emulsions containing 70%wt. oil.

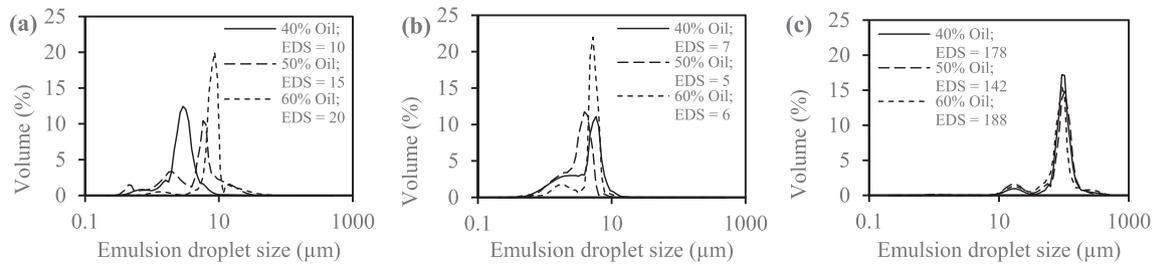


Fig. 2. DSD and EDS of O/W mayonnaise-like emulsions prepared by (a) SSPS, (b) GA, and (c) OSA-S as sole emulsifiers.

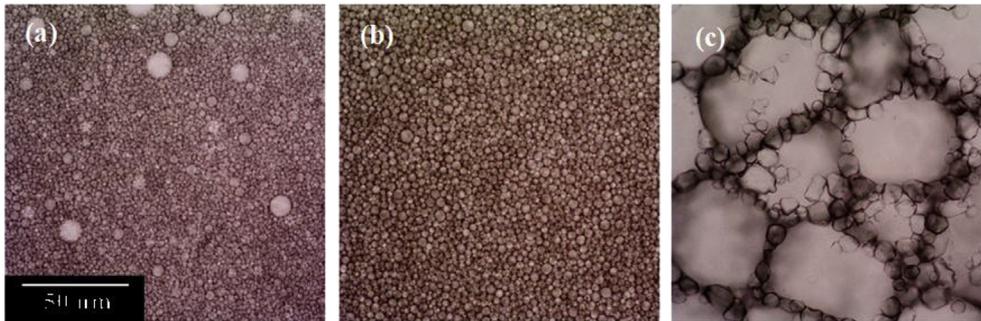


Fig. 3. Micrographs (x 40 magnification) of O/W mayonnaise-like emulsions prepared by SSPS (a), GA (b), and OSA-S (c).

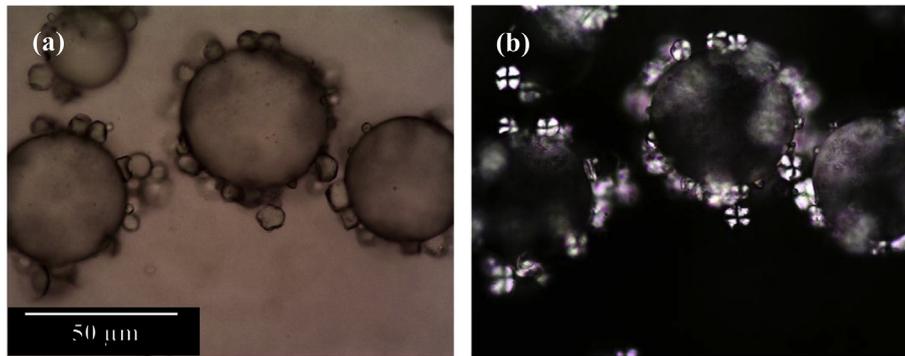


Fig. 4. Diluted O/W mayonnaise-like OSA-S stabilized emulsions showing starch granules at the oil/water interface. Adsorbed granules were observed under normal light (a) and polarized (b) microscopy.

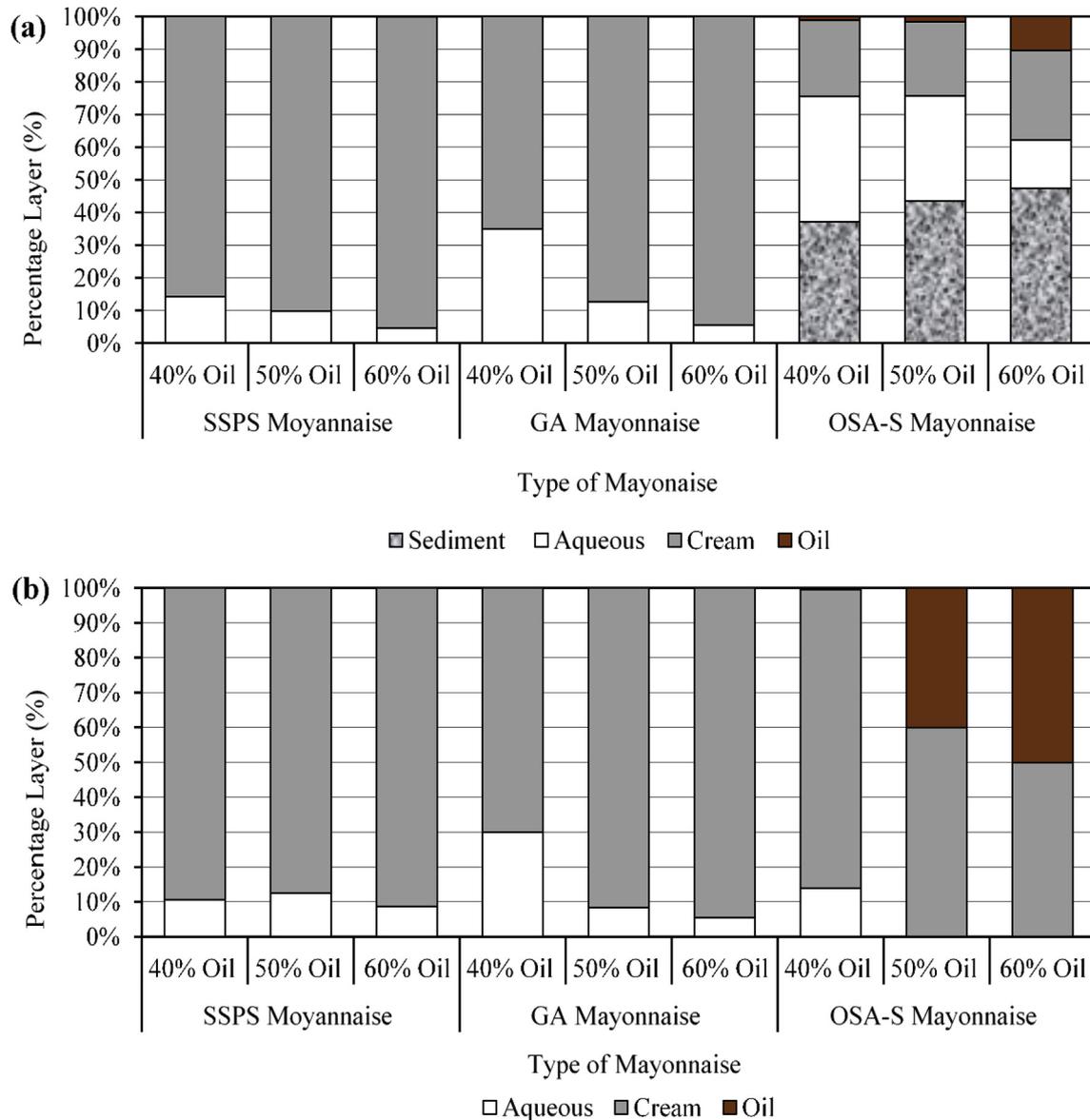


Fig. 5. Phase separation of (a) freshly prepared emulsions and (b) heat treated emulsions (80 °C for 30 min) under centrifugal forces.

droplets in the emulsion system. This slightly reduced the extent of syneresis in both SSPS and GA stabilized emulsion systems after being heated.

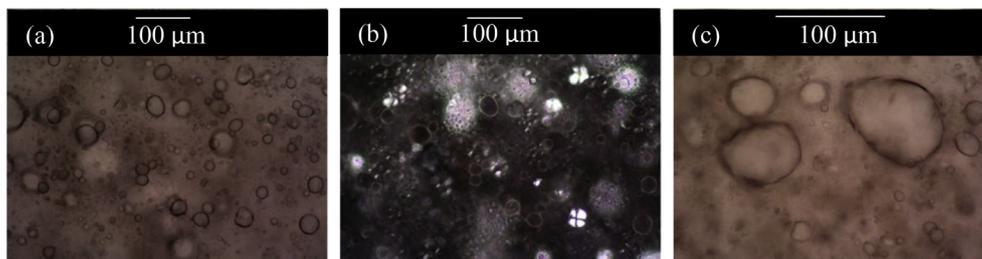
In the OSA-S stabilized emulsions, heating changed the emulsions significantly. At all oil concentrations, starch was partially gelatinized to form a gel-like emulsion as shown in Fig. 6a. Polarized microscopy (Fig. 6b) show some birefringence confirming the existence of intact granules within a mass of gel-like emulsion. Interestingly, oil droplets were found trapped within the network of starch as clearly shown by the micrograph in Fig. 6c.

Emulsions containing 40wt. of oil exhibited some syneresis, which was not observed in the other higher oil containing samples. Free un-adsorbed OSA-S granules gelatinized together with adsorbed granules forming a three dimensional network which helped to trap all the oil droplets (Marefati, Rayner, Timgren, Dejmek, & Sjöo, 2013). However, some free water existed in the sample and was squeezed out of the network by centrifugal forces. For emulsions containing 50 and 60wt. oil, destabilization and oiling off was observed leaving at least 50% cream layer in the

emulsion containing 60wt. of oil. In these emulsion systems, there was almost no free OSA-S granules – all granules were adsorbed at the interfaces. Upon heating, neighboring granules on oil droplet interfaces gelatinized together and in the process of forming a network, they were either pulled away from completely covering the oil droplets or formed very thin films around the droplets. As a result, centrifugal forces expelled the oil out of the starch network. Water was used up as starch granules were swelling up during gelatinization, hence no syneresis was observed.

### 3.3. Rheological properties

The apparent viscosity of all emulsions greatly decreased with an increase in the applied shear rate, a behavior characteristic of shear-thinning fluids. Plots of apparent viscosity against shear rate are shown in Fig. 7. Regardless of the oil content or emulsifier type, all emulsions exhibited an apparent shear thinning behavior. In concentrated emulsions, such as the ones prepared in this study, such pseudoplasticity represents an irreversible structural



**Fig. 6.** Normal light (a and c) and polarized light (b) micrographs of the cream phase collected after heat treatment and centrifugation of OSA-S stabilized O/W mayonnaise-like emulsions.

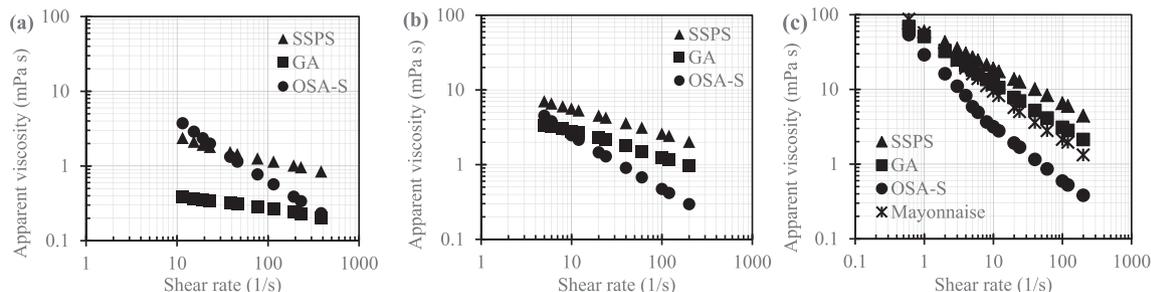
breakdown that may occur as a result of the spatial redistribution of the emulsion droplets under a shear field, or deformation and disruption of flocs (McClements, 2005). The extent of shear thinning behavior increased with increasing oil concentration. Emulsions with the highest concentration of oil (Fig. 7c) exhibited the highest degree of shear-thinning behavior due to disruption of the spatial organization of the emulsion droplets in the shear field. These results are consistent with the work reported by Nikovska (2010), who produced olive O/W emulsions stabilized by WPI and showed a typical non-Newtonian behavior with increasing dispersed-phase volume (70% v/v). Also, emulsions stabilized with OSA-S exhibited the most shear thinning behavior at all the tested oil concentrations. Similar to our findings, Dokic, Krstonosic, & Nikolic (2012) also reports the pseudoplastic behavior of emulsions stabilized by OSA-S when used as surfactant in sunflower oil O/W emulsions. Overall, the shear thinning behavior may have also been contributed by the presence of XG in the systems. It is known that XG forms highly ordered structures which are progressively disrupted with increasing shear, resulting in highly pseudoplastic flow characteristics of the emulsions (Nor Hayati, Che Man, Tan, & Nor Aini, 2007). Fig. 7c also shows a rheogram of normal mayonnaise purchased from a conventional Japanese supermarket in comparison to emulsions under investigation. It is evident that our prepared emulsion samples, especially GA emulsions, have rheological properties that are comparable to mayonnaise on the market.

Emulsions stabilized by SSPS had the highest apparent viscosity at all oil concentrations. This high viscosity in SSPS stabilized emulsions, in comparison to GA or OSA-S stabilized emulsions, also contributed to the stability of emulsions against centrifugal forces as seen in Fig. 5. Differences in the oil content affected the apparent viscosity of all the emulsion systems. In emulsions with lower oil contents, the emulsion droplets were far apart and the inter-particle interactions were relatively weaker. This structural conformation explains the low apparent viscosity of the systems

shown in Fig. 7a compared to the other two systems (b and c). As oil content increased, the emulsion droplets became closely packed and the inter-particle interactions became stronger, giving a non-Newtonian behavior. (Bellalta, Troncoso, Zúñiga, & Aguilera, 2012).

In Table 1, standard error values are shown for the different models applied to mayonnaise-like emulsions. The Bingham Plastic model had high standard error values and was therefore considered not a possible fit for these systems. The Casson model could not be used to estimate the flow behavior of OSA-S emulsions and GA emulsions with 60%wt. oil. Again, the Casson model did not seem to fit well with mayonnaise-like emulsions. Herschel-Bulkley model had the least error compared to other three models. There was however no clear pattern followed by the standard error values. The Power Law model showed high error values for OSA-S stabilized emulsions and this model was also considered not suitable for OSA-S emulsions, but most suitable for GA and SSPS stabilized emulsions systems. The Power Law model consistently gave consistency and flow behavior values that are in line with established rheological principles. The rheological parameters obtained from the Power Law model are shown in Table 2. The consistency indices increased with increase in oil concentration for each emulsifier type. Consistency index is an indicator of the samples viscous nature and hence, the trend shown by the Power Law model is consistent with the experimental results shown in Fig. 7. Flow behavior values also depict the extent of pseudoplasticity. Values far below unity indicate high pseudoplastic behavior (Nor Hayati et al., 2007).

On the other hand, even though the Herschel-Bulkley model gave the best overall fit, it returned some extraneous values for yield stress, i.e. SSPS emulsions with 50 and 60%wt. oil: -3.74 Pa and -11.53 Pa; GA emulsions with 40 and 50%wt. oil: -1.44 Pa and -3.59 Pa, respectively, which are not acceptable. Therefore, judging from the standard error values, the Herschel-Bulkley model was the most suitable for estimating OSA-S emulsions' parameters. The yield stress values for OSA-S emulsions as estimated by the



**Fig. 7.** Flow curves of freshly prepared O/W mayonnaise-like emulsions representing apparent viscosity as a function of shear rate. The emulsions differed in their oil contents, where systems containing 40, 50 and 60%wt. of oil are shown as a, b, and c, respectively. Rheograms of typical mayonnaise is plotted in comparison with hydrocolloid emulsion systems (c).

**Table 1**

Standard error estimates calculated from various rheological models for O/W mayonnaise-like emulsions.

Rheological Model	Mayonnaise type [Emulsifier/Oil content]								
	SSPS			GA			OSA-S		
	40%	50%	60%	40%	50%	60%	40%	50%	60%
Herschel-Bulkley	3.32	2.52	10.17	2.43	4.94	3.23	43.72	12.13	41.26
Bingham Plastic	31.16	52.28	81.86	32.03	53.97	81.50	91.23	82.62	65.52
Power Law	5.85	4.33	11.08	6.37	7.04	10.15	59.48	44.98	124.53
Casson	14.46	33.83	52.48	22.03	37.45	–	–	–	–

**Table 2**

Rheological parameters of O/W emulsions estimated by the Power Law (for SSPS and GA) and Herschel-Bulkley (for OSA-S) models.

Parameter	SSPS			GA			OSA-S		
	40%	50%	60%	40%	50%	60%	40%	50%	60%
Consistency Index (mPa s <sup>n</sup> )	2.09	12.92	60.19	0.68	6.65	44.89	3.93	3.86	1.47
Flow Behavior (–)	0.74	0.65	0.51	0.80	0.64	0.42	0.43	0.47	0.75

Herschel-Bulkley model were 12.41 Pa, 14.08 Pa and 28.88 Pa for emulsions containing 40, 50, and 60% oil contents, respectively. Consistency and flow behavior indices are shown in Table 2. Even though yield stress increased with increasing oil contents, consistency index was observed to show a decreasing trend. Simultaneously, the flow behavior indices became low at high oil contents, exhibiting opposite behavior when compared to the other two emulsion samples. It is expected for the consistency index to increase with increasing oil contents as seen for SSPS and GA stabilized emulsions due to increased inter-particle interactions in a system with closely packed emulsion droplets. This interesting anomaly observed for OSA-S emulsions is probably related to the structural features exhibited by closely packed Pickering emulsion droplets and is a subject for further studies.

#### 4. Conclusion

It is possible to produce O/W mayonnaise-like emulsions using hydrocolloid emulsifiers. Oil contents of up to a maximum of 60% wt. can be successfully incorporated into SSPS, GA or OSA-S stabilized emulsion systems although long term stability remains a problem, especially for OSA-S stabilized emulsions. Higher oil contents conferred an improved long term stability. Hydrocolloid emulsifier stabilized mayonnaise-like emulsion systems satisfied the Herschel-Bulkley and Power Law rheological models and showed an apparent shear thinning behavior similar to conventional mayonnaise. The results obtained in this study open new avenues into the replacement of egg yolk in production of mayonnaise. Future work should be focused on ways to improve the organoleptic properties of hydrocolloid emulsifier stabilized mayonnaise to produce a product similar to typical mayonnaise.

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