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Effect of different hydrocolloids on texture, rheology, tribology and sensory perception of texture and mouthfeel of low-fat pot-set yoghurt

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Abstract

A systematic study on the effect of some commonly used hydrocolloids in yoghurt formulation, namely gelatin (0.5-1.5%), xanthan gum (0.005-0.015%), carrageenan (0.01-0.08%) and modified starch (0.5-1.5%) on the physical, tribology and sensory characteristics of skim pot-set yoghurt (0.1% fat) is presented. The results support to develop a tribology model for yoghurt, which can be directly correlated with the scores on texture and mouthfeel attributes from sensory panel by mean of statistical analysis. The tribological behaviour, which signifies the lubrication property of the product, depended on the fat content, the type and dosage of hydrocolloid. Among the four hydrocolloids investigated, gelatin appeared to be the best hydrocolloid due to its ability to reduce syneresis, increase texture, viscosity, gel strength and lubrication properties of skim yoghurt. As a result, its sensory perception was significantly improved and attained the same sensory scores with full fat yoghurt for various desired sensory attributes, such as thickness, smoothness and creaminess. Both xanthan gum and carrageenan increased the firmness and viscosity of skim yoghurt, but also significantly increased the syneresis and undesired sensory mouthfeel characteristics, such as chalkiness and lumpiness. Modified starch slightly improved lubrication properties and thickness of skim yoghurt without significant changes in the product texture. From tribological analysis of investigated samples, a four-zone tribology model for yoghurt was proposed. Each zone corresponds to different mechanisms of fluid entrained between the two contact surfaces. The tribology behaviour of the yoghurt fluid, therefore, can be represented by the position of each transition point and the slope of each friction zone, which were aligned with the sensory scores from trained panel.

Keywords

Tribology, lubrication, friction, yoghurt, hydrocolloids, sensory
1. Introduction

Yoghurt is a widely-consumed fermented dairy food internationally and also renowned for its health benefits, nutritional value and digestibility (Desobry-Banon, Vetier, & Hardy, 1999; Shah, 2013). In recent years, non-fat and low fat varieties of yoghurt have become increasingly popular in the market. However, the omission of fat introduces a number of quality issues including poor, firm, texture and low viscosity, syneresis (whey separation due to partial denaturation of milk proteins during thermal treatment (Lee & Lucey, 2010)). It also leads to the reduction in smoothness and creaminess mouthfeels, which are both considered the most important consumer expectations for the texture of yoghurt (Lee & Lucey, 2010; Muir & Hunter, 1992).

To better combat the defects in texture, mouthfeel and physical properties commonly encountered in low fat yoghurt, researchers have investigated the broader effects of varying protein and fat levels, (Peng, Serra, Horne, & Lucey, 2009; Sodini, Remeuf, Haddad, & Corrieu, 2004) as well as processing, incubation and storage conditions (Keogh & O'Kennedy, 1998; Lee & Lucey, 2003; Lee & Lucey, 2004, 2010). Many different milk ingredients (e.g., nonfat dry milk, milk protein concentrate and whey protein concentrate) have been used in an attempt to improve texture by increasing the total solids content (Andić, Boran, & Tunçtürk, 2013; Teles & Flôres, 2007). Hydrocolloid stabilizers, such as gelatin, are often added to the milk base to maintain or enhance yoghurt properties including texture, mouthfeel, appearance, viscosity and consistency and to prevent whey separation (Fiszman, Lluch, & Salvador, 1999; Fiszman & Salvador, 1999; Lee & Lucey, 2010; Sanchez, Zuniga-Lopez, Schmitt, Despond, & Hardy, 2000; Schmidt & Smith, 1992). The rheological behavior of solution added hydrocolloids is affected by structural features of the hydrocolloid backbone and its side chains, molecular weight and conformation of the hydrocolloid molecules as well as solvent conditions (Norton, Spyropoulos, & Cox, 2011). However, there can be textural defects associated with the use of hydrocolloids. For example, over-stabilization can result in a “jello-like” springy body of yoghurt while a “runny” body or whey separation can be produced due to under-stabilization or improperly stabilization (Lee & Lucey, 2010).

For consumer, it is important that the hydrocolloids do not alter the natural flavour of the product and are effective at the typical pH range, 4.0–4.6. Considering these requirements, hydrocolloids that are often used include carboxyl methyl cellulose (CMC), pectin, alginate, and gelatin (Williams and Phillips, 2003). While the effects of different stabilizers and hydrocolloids on the textural and rheological properties of yoghurt have been well researched,
there has been limited study on their effects on lubrication properties and the association with corresponding sensory notes. Furthermore, there has not been a model for yoghurt tribology that describes the tribology behaviour by numerical parameters which can be directly correlated with the sensory scores for various textural and mouthfeel attributes.

To investigate the effect of fat level, three levels of milk fat concentration (0.1%, 1.3% and 3.8%) were used to make pot-set yoghurt; and to improve texture and sensory mouthfeel of skim yoghurt four popular hydrocolloids (gelatin, xanthan gum, carrageenan and modified starch) were chosen for the study. The change in texture, rheology, syneresis and lubrication properties of skim pot-set yoghurt with adding different levels of hydrocolloids were examined and compared against skim control and full fat yoghurts. The friction behaviours of the pot-set yoghurt will be analysed and fit into a representative model which will be then translated into numerical tribological parameters. These parameters, together with other textural and rheological factors of yoghurt, will be directly related with sensory scores obtained from trained panel by means of statistical analysis.

2. Materials and Methods

2.1. Materials

Three different types of commercial pasteurized and homogenized milk of varying fat content (0.1%, 1.3% and 3.8%), which are the three standard fat levels in milk available in the Australian market, were used for yoghurt production. Freeze-dried direct vat set (FD-DVS) culture YC-X11 obtained from Chr. Hansen Pty. Ltd. (Australia) was used as a starter culture, activated with UHT full cream milk (3.4% fat).

Edible bovine gelatin powder (140 bloom) was purchased from GELITA Australia Pty. Ltd., Australia and κ-carrageenan (SEAKECM611) was purchased from IMCD Australia Ltd., Australia. Other hydrocolloids: xanthan gum and modified starch (Ultra Sperse M Starch Powder) were purchased from The Melbourne Food Ingredient Depot, Australia. The modified starch was hydroxypropyl starch phosphate (100%) derived from waxy maize.

2.2. Pot-set yoghurt production

Pot-set yoghurt production followed the procedure recommended by Chr. Hansen Pty. Ltd. (Australia) and Andić, Boran, and Tunçuğurk (2013); Hematyar, Samarin, Poorazarang, and Elhamirad (2012). Pasteurized milk was heated to 85 °C for 30 minutes before being cooled.
to the incubation temperature (43 °C). If any hydrocolloid was used, during thermal treatment step, the hydrocolloid was slowly added and stirred into skim milk using overhead stirrer until they were completely dissolved. 50 units of direct vat set culture was first diluted in 500 mL of the UHT milk at 43 °C, from which 2 mL of solution was added to 1 L of tempered milk or yoghurt formulation. The yoghurt milk was filled into 90 mL sterile glass containers and incubated in water bath at 43 °C for 4-6 hours until the pH reached to 4.6-4.7. Then the samples were refrigerated at 4 °C to reduce post-acidification for two days before instrumental measurement and sensory evaluation. The pH after two-day storage slightly reduced to 4.5-4.6.

As reported previously (Ares, et al., 2007; El-Sayed, Abd El-Gawad, Murad, & Salah, 2002; Hematyar, Samarin, Poorazarang, & Elhamirad, 2012) and from our preliminary trials, it was found that each hydrocolloid can increase the yoghurt firmness and reduce the syneresis of skim yoghurt (0.1% fat) at a certain range of concentration. Accordingly, the chosen concentration of each hydrocolloids to be added in the skim yoghurt were: gelatin (0.5 – 1.5%), xanthan gum (0.005 – 0.015%), κ-carrageenan (0.01 – 0.08%) and modified starch (0.5 – 1.5%).

2.3. Texture measurement

A Texture Analyser (TA-XTplus, Micro Stable System Co., UK) was used to determine the firmness/hardness of yoghurt samples. Penetration test was carried out using a cylinder probe 10 mm in diameter to apply 15 mm penetration on pot-set yoghurt samples at the speed of 1 mm/s and the trigger force of 5 g. The measurements were made immediately after removal from the fridge (4 °C).

2.4. Syneresis measurement

Syneresis in the yoghurt samples was measured using the centrifuge method described by (Keogh & O'Kennedy, 1998), but with a higher centrifugal force and longer time. 30 g of yoghurt sample was centrifuged at 300 g for 20 min at 4°C (Eppendorf Centrifuge 5702 R USA). After centrifugation, the clear supernatant was poured off, weighed and used to determine the percentage (w/w) of syneresis.

2.5. Confocal scanning laser microscope

Liquid whey after centrifugation step in syneresis measurement was collected and analysed using confocal scanning laser microscope to study the distribution of fat and protein. The
protein and fat phase were stained by mixing liquid whey with 0.01% Rhodamine B and 0.01% Nile Red solutions, respectively.

2.6. Rheological measurement

Viscosity of the yoghurt samples was measured under steady state shear conditions by shear rate-controlled rheometer (Discovery Hybrid Rheometer, TA Instrument, USA) using 60 mm stainless steel parallel plates at 100 µm gap, with shear rate ranging from 0.1 to 1000 s⁻¹. A solvent trap cover and a standard Peltier plate with solvent trap filled with deionized water were used to mitigate sample drying during the experiment. The pot-set yoghurt (in 90ml glass container) was equilibrated at room temperature (22-25°C) for 1 hour, then gently stirred by a stainless-steel spatula to eliminate any phase separation before measurement. At the beginning of each test, the sample was equilibrated again for 60 s at 35°C between the parallel plates at the measurement gap.

The storage modulus (G’) and loss modulus (G”) of yoghurt samples were measured by small amplitude oscillatory rheology test at the same gap and temperature in the linear viscoelastic region, at constant strain of 0.1 % for the angular frequency ranging from 0.01 to 1000 rad/s. All tests were performed at 35 °C and conducted in triplicates.

2.7. Tribological measurement

Lubrication properties of yoghurt samples were measured on a Discovery Hybrid Rheometer, using ring-on-plate tribo-rheometry (TA Instrument, USA) on a rough plastic surface of 3M Transpore Surgical Tape 1527-2 (3M Health Care, USA). The tribometer configuration has been presented schematically elsewhere (Nguyen, Bhandari, & Prakash, 2016). A half-ring rheometry, which is a stainless-steel ring interrupted in three sections such that only half of the ring is in contact with the substrate, was used to permit the replenishment of lubricant between the two solid surfaces. The tongue surface was modelled using 3M Transpore surgical tape which was reported to have similar wettability and surface roughness to human tongue (Nguyen, Nguyen, Bhandari, & Prakash, 2016). The tape was cut in a square shape, placed and pressed firmly on top of the lower plate rheometry. After each measurement, the tape was replaced and the tribo-rheometry was cleaned and dried with deionised water and laboratory wipes. The reliability of this tribometer set-up has been previously validated to be able to analyse and discriminate dairy products with different fat contents in both liquid and semi-solid forms (Nguyen, Bhandari, et al., 2016).
The yoghurt sample was equilibrated at room temperature (22 - 25°C) for 1 hour before the
tribology measurement was performed at 35 °C to simulate the oral condition. Since in-mouth
force has been reported to be between 0.01 – 10 N (Miller & Watkin, 1996), we used a
constant normal force of 2 N (i.e. pressure 27.83kPa) to represent the moderate normal force
applied on the sample during oral processing. 2 g of sample was used for each test, which was
gently spread to completely cover the lower plate surface with an approximate 1 mm
thickness. The samples were pre-sheared at 0.01 s⁻¹ for 1 minute, and then equilibrated for
another 1 minute before each measurement. The friction results between the tribo-rheometry
and the tape surfaces were recorded for rotational speeds from 0.01 to 100 s⁻¹ with 20 points
per decade. All measurements were conducted in triplicates.

Tribological data were screened so that data points with normal forces error greater than 5%
of the set values were removed from the analysis. The friction force ($F_F$), friction stress ($\sigma_F$)
and friction coefficient ($\mu$) between the two contact surfaces were calculated using equations
reported elsewhere (Nguyen, Bhandari, et al., 2016).

### 2.8. Sensory analysis

Sensory evaluation was conducted by eight trained panelists (4 males, 4 females, age 20–40
years, healthy subjects, lactose tolerant) using quantitative descriptive analysis (QDA®). They
have been selected after completing scaling exercise and basic tastes and texture exercise as
per ISO 22935. The panellists generated the textural attributes (Table 1) associated with
commercial pot-set yoghurts during the training sessions (30 hours) which were later used to
evaluate the texture of the in-house pot set yoghurt samples. For each textural attribute,
commercial pot-set yoghurts with low and high intensity were provided as anchor points
during training sessions. Panelists evaluated the in-house samples using a linear scale with
increasing score from 0 to 15 with anchors marked at 1.25 cm from either end. Panelists were
allowed to use different parts of the scale to determine the sensory score by themselves. As a
result, the difference in scores among products is always relative. In a properly designed
study, however, and with correctly trained panellists, this difference between panellists is
taken out in the analysis. Panellists’ internal consistency and the reproducibility of the panel
are assessed on the basis of repeated evaluations of the same products. The evaluation was
conducted in individual sensory booths.

Only six yoghurt samples were chosen for sensory analysis: skim yoghurt, full fat yoghurt and
four skim yoghurts with added hydrocolloids (one concentration for each hydrocolloid) which
have the closest texture and rheology characteristics with full fat yoghurt, the least syneresis, the highest lubrication properties in tribology tests and acceptable sensory perception during a preliminary screening session. A randomized complete block design (panelists as blocks) with six samples was used to compare the yoghurt sensory attributes. Equal amounts of each pot-set yoghurt were prepared in 90 mL glass container labelled with randomly selected 3-digit codes and equilibrated at room temperature for at least 1 h before consumption. The samples were served to panelists with spoon and with spring water for palate cleaning. Test procedure and data collection were programmed using Compusense® software.

2.9. Statistical analysis

For all the physical tests, experimental data were assessed by one-way ANOVA with Minitab® 17 and Tukey test for pairwise comparison to determine the significant differences among the in-house yogurt products. The product means were considered to be significantly different when $P<0.05$.

For sensory analysis, multivariate data analysis and mixed linear model analysis (panelists and sessions as random factors) were used to assess the performance of the panel, to draw conclusions about samples from sensory evaluations. The analysis was conducted with the corresponding procedures in Minitab® 17 (Minitab Inc., Chicago). The principle component analysis based on sums of squares was performed with GenStat 17 (VSN International Ltd, UK) on a complex of sensory scores for 6 pot-set yoghurt samples.

3. Results and Discussions

This work investigated the effect of fat content and different hydrocolloids on the tribology and sensory characteristics of the pot-set yoghurt. In order to understand the mechanism and compare with conventional yoghurt quality attributes we also determined the rheology, textural characteristics and syneresis behaviour of the yoghurt samples.

3.1. Textural and rheological properties of yoghurt

3.1.1. Texture analysis

The firmness of the yoghurt samples are presented in Table 2. Comparing samples with different fat contents, it is clearly seen that the firmness increased with fat content. The skim and trim yoghurt has similar firmness which is due to their similar protein content. Due to the heat treatment of milk (at 85°C for 30 minutes), a gel structure with a cross-linked microstructure is formed by denatured whey proteins associated with the casein micelles that
governs the gel strength and texture of the yoghurt (Lee & Lucey, 2003; Lucey, Munro, & Singh, 1998). Therefore, protein content appears to be the governing factor for a stronger gel network which makes the product firmer.

However, when there are more fat particles (in the case of full fat sample) in the system, the fat itself also plays a role in the firmness of the product. Fat globules interact with each other and with denatured whey proteins associated with casein micelles in the serum during acidification, thereby increasing the cross-linking density of acid gels. Furthermore, whey proteins can adsorb onto the fat globule surface and enhance the interaction among themselves (Lucey, et al., 1998). As a result, the higher population of fat globules in the matrix could lead to the development of multiple interactions between fat globules, whey proteins, and casein micelles that strengthens the three-dimensional gel network (Aguilera & Kessler, 1989). This is the reason why full fat yoghurt (3.8% fat) has a firmer texture as compared to lower fat samples. In trim yoghurt, the number of fat globules is not enough to strengthen the gel network and the texture is therefore governed by protein – protein interactions.

When adding different hydrocolloids, in general, the firmness of the skim yoghurt increased in proportion to the concentration of hydrocolloid. Among them, xanthan gum and carrageenan significantly increased firmness of the sample even at a small concentration (less than 0.1%) while a relatively higher level of gelatin and modified starch is required to increase firmness. The increase in texture when adding xanthan gum and carrageenan is in agreement with previous studies (El-Sayed, et al., 2002; Sanchez, et al., 2000). The mechanism of increasing the yoghurt firmness varies among the hydrocolloids. Carrageenan and xanthan gum, negatively charged hydrocolloids at low pH condition, interact with the positive charge on the surface of casein micelles (Hansen, 1993; Hemayyar, et al., 2012) to form highly structured and open protein networks (Sanchez, et al., 2000). Modified starch, on the other hand, is a neutral stabilizer, does not undergo pH-dependent interactions with the proteins, but improves body and texture by increasing the viscosity of the aqueous phase of the system (Hansen, 1993). Gelatin interacts with casein matrix and connects the casein micelle aggregates and chains of milk proteins to build a firmer three-dimensional deformable system (Andiç, et al., 2013; Fiszman, et al., 1999; Fiszman & Salvador, 1999). In order to achieve similar firmness of full fat yoghurt, the amount of hydrocolloid required to add into the skim yoghurt were 0.5% gelatin, 0.01% xanthan gum, 0.04% carrageenan or 0.5% modified starch.
3.1.2. Syneresis

The syneresis or whey separation property of the yoghurt samples is presented in Table 2. It was observed that trim and skim yoghurt samples had a similar percentage of syneresis and it is much more than the full fat sample. This is because in the presence of more fat globules, protein adsorbs on the surface of the fat globules making milk fat globules act like protein particles and increases its ability to immobilize water (Becker & Puhan, 1989; Keogh & O’Kennedy, 1998; Lee & Lucey, 2010). In this system, higher populations of fat globule in the gel network improve its ability to hold water and make it less prone to syneresis. The results obtained in our study are consistent with previous work on water holding capacity of yoghurt samples with different fat levels (Becker & Puhan, 1989; Keogh & O’Kennedy, 1998).

When adding different hydrocolloids, the syneresis percentage of the skim yoghurt changed differently. While gelatin significantly reduced the syneresis to almost zero percent, the reverse effect was observed for other hydrocolloids. Xanthan gum and carrageenan doubled the syneresis of the skim sample at a very low concentration (less than 0.01% for xanthan gum and 0.1% for carrageenan) while adding up to 1.5% modified starch could only change its syneresis slightly. These observations are in agreement with the previous studies on the yoghurt and acid milk gel syneresis when adding the same hydrocolloids (Andić, et al., 2013; Ares, et al., 2007; Fiszman, et al., 1999; Keogh & O’Kennedy, 1998; Pang, Deeth, & Bansal, 2015; Pang, Deeth, Sharma, & Bansal, 2015).

In the samples with added gelatin, it is suggested that gelatin interacts with the casein matrix and connects the casein granules and chains of milk proteins to build a complex interconnected network which retains the aqueous phase more efficiently, hence reducing the drainage of liquid (Andić, et al., 2013; Ares, et al., 2007; Fiszman, et al., 1999; Fiszman & Salvador, 1999). Adding xanthan gum and carrageenan also strengthens the interconnected protein network but, on the other hand, leads to more syneresis due to depletion flocculation (Hemar, Tamehana, Munro, & Singh, 2001). A highly porous casein particles network is formed leading to wheying-off and casein network shrinkage (Sanchez, et al., 2000).

Samples manufactured with the addition of 0.5% of starch showed similar syneresis values as the skim control sample. However, the addition of higher levels of starch reduced syneresis down to 12%. This reduction in syneresis was due to the ability of starch granules to absorb water and swell into much bigger sizes (Ares, et al., 2007).
3.1.3. Rheological behavior

The viscosities of pot-set yoghurt of different fat levels are presented in Figure 1. All the three yoghurt exhibits shear thinning behavior (Lee & Lucey, 2010) for the shear rates from 0.1 to 1000 s\(^{-1}\). However, the viscosity profiles for these samples almost overlapped at most shear rates.

When adding hydrocolloids into the skim yoghurt, different effects were seen on viscosity, depending on which hydrocolloid was used (Figure 2). Carrageenan and xanthan gum significantly increased the viscosity at very low concentrations (less than 0.02% for xanthan gum and 0.1% for carrageenan) while the viscosities of the samples with added modified starch remained the same as the skim yoghurt. Interestingly, gelatin significantly decreased the yoghurt viscosity and this effect increases with the concentration of gelatin.

Viscosity at shear rate of 50 s\(^{-1}\) has been suggested to have a good correlation with perceived thickness, stickiness and sliminess for a wide range of food products from Newtonian fluid to thick emulsion (Shama, Parkinson, & Sherman, 1973; Shama & Sherman, 1973; Wood, 1968). Therefore, we presented in Table 2 the viscosity values at the shear rate of 50 s\(^{-1}\) (\(\eta_{50}\)) for all the yoghurt samples. No significant difference (P>0.05) were observed between the \(\eta_{50}\) values of yoghurt samples at different fat levels. Similar observations were made for skim yoghurt with different levels of modified starch suggesting that modified starch does not significantly change the viscosity of the skim yoghurt as compared to the control sample. Both xanthan gum and carrageenan substantially increased the \(\eta_{50}\) of the skim yoghurt at very low concentrations: 0.015% for xanthan gum and 0.08% for carrageenan. In contrast to other hydrocolloids, adding more gelatin resulted in a reduction of the apparent viscosity \(\eta_{50}\) for the skim yoghurt.

Figure 3 shows the storage modulus (\(G'\)), loss modulus (\(G''\)) and loss tangent (\(\tan \delta = G''/G'\)) for the yoghurt samples of different fat levels. Trim and full fat samples had the same \(G'\) and \(G''\) values for most frequencies in the examined range and these values were significantly lower than skim yoghurt. The \(\tan \delta\) value of the sample decreased in the order from skim, trim to full fat product, indicating that the yoghurt samples became more solid-like with increasing fat content. This is consistent with the results in section 3.1.1 that the full fat sample had the firmest texture. The lower values of \(G'\) and \(G''\) for trim and full fat sample as compared to the skim one can be explained by the interspersion throughout the protein network of the fat.
particles that reduces the gel strength of the high fat samples when the sample is being
sheared dynamically at 35 °C.

When adding different hydrocolloids, the gel network structure changed accordingly. Adding
gelatin reduced both G' and G" of the skim yoghurt and this reduction became more
significant with greater addition of gelatin. At the addition level of 1.5% gelatin, the G' and
G" values reduced to one order of magnitude lower than the control skim sample (Figure 4a).
Both xanthan gum and carrageenan have the ability to interact with milk protein in the
yoghurt gel network to increase viscosity, G' and G" considerably (Schmidt & Smith, 1992).
To achieve the same viscosity and gel strength, more carrageenan was needed as compared to
xanthan gum (Figures 4b & c). The optimum concentration of xanthan gum was 0.01%, above
which the gel strength did not increase further. For the samples with added carrageenan, the
moduli slightly dropped at the concentration of 0.01%, then increased sharply with increasing
level of carrageenan. This behavior appears to be repeatable and the reason is unknown.
Adding modified starch slightly reduced the moduli of the yoghurt sample, but it did not
reduce further at higher concentrations.

Thus, adding different hydrocolloids had the same effect on viscosity as on gel strength. This
is due to the underlying changes in the internal structure of the yoghurt sample that affect its
rheological properties. As discussed earlier, negatively charged xanthan gum and carrageenan
interact with the positively charged surface of the casein micelles to form a highly structured-
network which contributes to the increase in the sample viscosity and gel strength (Norton, et
al., 2011; Soukoulis, Panagiotidis, Koureli, & Tzia, 2007). At high concentrations of these
hydrocolloids, the casein aggregates may be trapped within the increasingly viscous
polysaccharide solution explaining the big increase in apparent viscosity (El-Sayed, et al.,
2002; Hansen, 1993; Hematyar, et al., 2012). Starch on the other hand has a totally different
thickening mechanism unlike hydrocolloids. Modified starch granules imbibe water and swell
to many times of their original size, resulting in increased viscosity of the solution (Ares, et
al., 2007), but do not significantly increase the storage and loss moduli of the skim samples at
our examined concentrations.

The most interesting observation was on the rheological behavior of the samples with added
gelatin. It is believed that gelatin interacts with the casein matrix and connects the casein
micelle aggregates and chains of milk proteins to build a firmer three-dimensional deformable
system (Andiç, et al., 2013; Ares, et al., 2007; Fiszman, et al., 1999; Fiszman & Salvador,
1999). This is consistent with the improvement seen in the texture profile and water holding
capacity mentioned in sections 3.1.1 and 3.1.2. However, viscosity and gel strength measurements were performed at 35°C, in order to mimic oral conditions. This temperature is close to the melting point of gelatin (Djabourov, 1988) that gelatin may melt during the measurement, leading to the smooth reduction of viscosity and gel strength as the samples are being sheared. The higher the level of added gelatin, the more dominant this effect is; therefore, the more reduction in the sample viscosity and gel strength. This mimics exactly what happens with the oral condition when the yoghurt sample is being manipulated between the tongue and palate to create a smooth and fat-like mouthfeel. This is a distinct behavior of gelatin that is absent in other stabilizers and hydrocolloids (Salvador & Fiszman, 1998).

The rheological properties examined so far can only shed light on the bulk fluid behavior of sample as like when it first enters the mouth. However, subsequent oral processing involves compression of tongue against other oral surfaces during which the food no longer behaves like a bulk fluid, but rather acts as a thin film (Chen & Stokes, 2012). Moreover, it has been observed that some aspects of sensory mouthfeel, especially those related to fat content, do not correlate with the sample viscosity, but rather its lubrication properties (Baier, et al., 2009; Kokini, 1987; Kokini & Cussler, 1983; Malone, Appelqvist, & Norton, 2003). For semi-solid fluid like yoghurt, these sensory mouthfeel factors could be smoothness, creaminess, oiliness and fatty feel which are usually absent for low fat products (Baier, et al., 2009; Giasson, Israelachvili, & Yoshizawa, 1997; Joyner, Pernell, & Daubert, 2014; Malone, et al., 2003; Sonne, Busch-Stockfisch, Weiss, & Hinrichs, 2014). Therefore, in the next section, we investigate the effect of the hydrocolloids on the lubrication properties of yoghurt by means of tribology tests.

3.2. Tribological behavior and model

Tribological behaviour or lubrication properties of a sample can be presented as a friction curve, namely the Striebeck curve. Traditionally, this curve is divided into three regimes: boundary, mixed and hydrodynamic (Prakash, Tan, & Chen, 2013). In boundary regime, the friction between the two contact surfaces is hardly affected by the sliding speed or the lubricant viscosity, but by the ability of the sample to adsorb and form a lubrication film between the surfaces (Butt, Graf, & Kappl, 2004); therefore, the friction is constant. With increasing speed, a hydrodynamic film is created that significantly reduces the friction, i.e., the Striebeck curve enters into the mixed regime. This reduction of friction is governed by the sample viscosity that promotes fluid entrainment (Cassin, Heinrich, & Spikes, 2001). At even
higher speeds, the hydrodynamic film is fully developed and completely separates the surfaces, i.e. hydrodynamic regime. The friction is governed by the internal friction (or viscosity of fluid) and increases linearly with speed (Butt, et al., 2004; Williams, 2005).

However, for the yoghurt samples used in our study, the internal structure was more complex with liquid whey and cross-linked gel network formed by denatured whey proteins associated with the casein micelles, in which fat globules were entrapped. The friction curves (Figure 6) did not resemble the traditional Stribeck curve, but rather followed the schematic diagram in Figure 5. The friction curve can be generally divided into five zones:

(i) Zone 1: the gap between the two contact surfaces is very narrow so that only liquid whey can enter the contact zone. The friction behaviour in this zone is governed by the soluble substances and small-dispersed particles in the liquid whey such as whey protein and free fat globules, which migrated from the gel matrix. When there is enough population of free fat globules, the friction reduces gradually from dry contact to a minimum value at transition point $T_1$.

(ii) Zone 2: the fluid (in the gel form) starts to entrain into the contact zone which gradually increases the friction. A thin lubrication film between the contact surfaces is developing that increases the friction to its maximum value (transition point $T_2$). The friction is no longer a constant value like the conventional Stribeck curve, but rather increases linearly with speed.

(iii) Zone 3: the lubrication film develops further and increases in thickness that can partly separate the surfaces and reduces the friction. The reduction of friction is governed by the sample viscosity that promotes fluid entrainment (Cassin, Heinrich, & Spikes, 2001). This regime is the same as the mixed regime in the conventional Stribeck curve.

(iv) Zone 4: the friction curve changes in slope at transition point $T_3$. If the fluid retains its structure, the friction may achieve another local minimum at the end of mixed regime (transition point $T_3$) and increases again with increasing speed. The hydrodynamic film is fully developed and completely separates the surfaces, i.e. this is the same as hydrodynamic regime in traditional Stribeck curve. The friction is now governed by the internal friction (or viscosity of fluid) and increases linearly with speed (Butt, et al., 2004; Williams, 2005). On another hand, if the fluid structure breaks down at high speeds, the friction may reduce further with speed. Thus, the
behaviour of fluid within this zone is not solely governed by the sample viscosity, but rather the gel strength of the sample.

Since yoghurt is in the form of soft gel structure, its lubrication behavior is very similar to fluid gel. Therefore, the shape of friction curve observed in this work is very similar to that of agarose gel solution reported by (Gabriele, Spyropoulos, & Norton, 2010) excepting there is an additional zone 4 (Figure 5).

In order to quantify behavior of friction in each zone, we defined \( v_i, f_i \) are the speed (mm/s) and friction coefficient at the transition point \( T_i \), and \( s_i \) is the slope of zone \( i \) (assuming linear relationship between logarithm of friction and logarithm of entrainment speed in each zone), in which \( i=(1,4) \). It should be noted that friction curve for each zone might not be linear, we only used slope as a representative parameter to describe the relative change of friction as a function of entrainment speed which could be positive or negative depending on each zone. Values of these parameters for all yoghurt samples are reported in Table 3.

We first investigated the lubrication properties of yoghurt samples with different levels of fat: skim (0.1% fat), trim (1.3% fat) and full fat (3.8% fat) and the friction curves are shown in Figure 6. It is seen that all four zones were observed for trim and full fat yoghurts while zone 1 was missing for skim yogurt. Zone 1 for skim yoghurt may not exist or occur at the speeds lower than 0.01 mm/s below which the normal force was not maintained efficiently within this tribometer set up.

Generally, skim yoghurt has a significantly higher friction coefficient than the higher fat ones for all zones. The zone 4 and a fraction of zone 3 for trim and full fat samples overlapped while friction values in zones 1 and 2 for the trim sample were slightly higher. Furthermore, the friction value of skim yoghurt decreased in zone 4 while higher fat yoghurts have an increased friction in zone 4.

Comparing the friction behaviours of the three yoghurts with dry contact (no sample) and water (Nguyen, Nguyen, et al., 2016), it is seen that the onsets of zone 1 for yoghurt samples were the same with dry contact and water (friction coefficient of approximately 0.15 at a sliding speed of 0.02 mm/s) indicating that for all cases there was no fluid between the two contacts. As the speed increased, the frictions of water and yoghurts became lower than dry contact which indicated the presence of fluid in the contact zone. Trim sample followed similar trend with water while the friction for full fat sample decreased rapidly to lower values. Since the speeds in zone 1 were very low (less than 0.2 mm/s), only liquid whey could...
enter the contact zone. The different friction behaviours, i.e. different lubrication properties, could be due to the composition of liquid whey of which higher fat yoghurt contained higher fat content as indicated by an increase in the fat globule population and fat globule size in the liquid whey from skim, trim to full fat yoghurt shown in confocal laser scanning microscope images in Figure 7. For the skim yoghurt, the liquid whey contained mainly protein and negligible amount of fat globule which gave a much higher friction than water; while the presence of fat globules in full fat sample made its whey much more lubricated than water. Trim and water had similar frictions indicating that liquid whey of the trim yoghurt entrained into the contact zone has similar friction with water. The mechanism of friction change due to different protein/fat contents could be explained by the adsorption of protein or/and fat on the bottom surface which has been discussed elsewhere (Nguyen, Nguyen, et al., 2016).

In the beginning of zone 2, the friction for the three yoghurts increased due to the entrainment of yoghurt gel into the contact zone to form a lubricating film whose thickness is in the same order of magnitude with the tape roughness (Ra=31.5µm) (Nguyen, Nguyen, et al., 2016). The friction values decreased in the order from skim, trim to full fat yoghurts due to an increase in fat level in the samples that lead to the rise of population of fat globules in the lubricating film entrained into the contact zone between the two surfaces.

After reaching the maximum friction (at transition point $T_2$), the friction entered zone 3 and decreased with speed due to entrainment of more yoghurt gel to develop a thicker lubrication film that partly separated the surfaces. The friction was governed by both thin film and hydrodynamic lubrication. Slopes of the zone 3 ($s_3$) for trim and full fat yoghurts were the same (~0.19) (Table 3) which indicated their similar lubrication behaviour in this zone.

From transition point $T_3$, both friction curves for trim and full fat yoghurt increased linearly with speed, i.e. $s_4$ is positive, indicating hydrodynamic lubrication (Butt, et al., 2004). Since the friction in zone 4 was governed by fluid viscosity (Butt, et al., 2004), the overlapping of trim and full fat samples in this zone indicated their similar gel structure and viscosity which are in agreement with the results presented in section 3.1.3. Different from the high fat yoghurts, $s_4$ for the skim yoghurt decreased further, indicating a structure breakdown of the skim yoghurt at high speeds.

It is interesting to note that the entrainment speeds at transition points $T_2$, $T_3$ and $T_4$ were similar between trim and full fat yoghurt while those for skim yoghurt shifted to lower values. This shift of the transition points may be due to the higher elasticity (higher G’ value in
Figure 3) of skim yoghurt which allowed the fluid gel easier to entrain into the contact zone, i.e. a lower speed was required to entrain the fluid. Trim and full fat yoghurts had similar elasticities (Figure 3), therefore, had similar critical entrainment speeds. Same behaviour was observed for agarose fluid gel solution with different particle elasticities (Gabriele, et al., 2010).

We next investigated the tribology of skim yoghurts modified with different hydrocolloids. It is seen in Figure 8 that for all samples zone 1 was not observed and most of the changes in friction occurred in zones 2 and 4. The reason of missing zone 1 for those samples might be similar to skim that zone 1 might not exist or it occurred at the speeds lower than 0.01 mm/s or this.

For samples with added gelatin (Figure 8a), it can be seen $f_2$ reduced slightly with increased gelatin concentration. This could be due to the melting properties of gelatin at 35 ºC that enhanced the thin film lubrication of the sample in the zone 2. Furthermore, $s_3$ (negative value) increased with higher levels of gelatin indicating less fluid entrainment into the contact zone because of the decrease in gel viscosity. This observation is in agreement with the reduction in viscosity and gel strength of the gelatin-added sample described in section 3.1.3. However, $s_4$ increased from negative to positive values when adding more gelatin, indicating higher hydrodynamic lubrication. This effect is believed to be governed by the higher viscosity, which appears to contradict the observations on the rheological properties in the previous section. One possible explanation for this is that, at low speeds, the viscosity decreased with more addition of gelatin which was due to the melting phenomenon; however, at higher speeds, the viscosity was governed by the strength of the gel network which was strengthened by the interaction between gelatin and the protein network (Andić, et al., 2013; Ares, et al., 2007; Fiszman, et al., 1999; Fiszman & Salvador, 1999). Therefore, adding gelatin reduced the sample viscosity at low entrainment speeds, but enhanced the sample stability at high speeds, which corresponded to the hydrodynamic regime.

Xanthan gum did not significantly change the friction in zones 2 and 3, but increased the slope of zone 4, $s_4$, when being added up to a concentration of 0.010% (Figure 8b). Adding more xanthan gum (0.015%) appeared to shift the lubrication properties of the yoghurt sample back toward the control condition. Since xanthan gum only changed the friction behavior in zone 4, the lubrication property of the skim yoghurt was improved only by enhancing sample viscosity. This is confirmed by the overlapping friction curves of the xanthan-added samples.
in Figure 9, when replotting the friction curves in Figure 8b as a function of a combined parameter of entrainment speed and effective viscosity (i.e. sample viscosity in Figure 2 at the shear rate of 1000 s$^{-1}$).

For the samples with added carrageenan (Figure 8c), there was no significant change in zones 2 and 3, but the slope of zone 4 ($s_4$) reduced significantly to negative values and this effect was irrespective of the concentration of the hydrocolloids. This might be due to a structural breakdown of the yoghurt samples when adding carrageenan that made the products less stable at high entrainment speeds.

Modified starch appears to have a very similar effect to gelatin in changing the lubrication properties of the skim yoghurt. Adding different levels of modified starch significantly increases the slopes of zone 2 ($s_2$) and zone 4 ($s_4$). The increase of $s_4$ indicates the increase of yoghurt viscosity at high speeds. This contradicted the observations on the texture and bulk rheological properties in the sections 3.1.1 and 3.1.3 which show negligible improvement in sample viscosity when adding modified starch. Liu, Stieger, van der Linden, and van de Velde (2016) also observed some changes in boundary and hydrodynamic regimes when adding native and gelatinized rice starch in liquid and semi-solid material. Those changes were believed to govern by viscosity and “stickiness properties” of the fluid rather than lubrication.

3.3. Sensory analysis

Selected skim yoghurt samples with added hydrocolloids were evaluated in sensory analysis in comparison to the full fat and skim yoghurts. The samples selected demonstrated low syneresis and textural characteristics similar to those of the full fat yoghurt (Table 2): 0.5% gelatin (skim gelatin hereafter), 0.01% xanthan gum (skim xanthan), 0.01% κ-carrageenan (skim carrageenan), and 1% modified starch (skim modified starch). Each of the yoghurts were tested for the 8 major sensory attributes (Table 1); the sensory scores are presented in the spider diagram in Figure 10. It is seen that full fat yoghurt has significantly higher scores in smoothness, thickness, creaminess compared to skim yoghurt. This is in agreement with the higher firmness and effective viscosity $\eta_{50}$ of full fat yoghurt reported earlier in section 3.1. The higher score in creaminess of full fat yoghurt compared to skim yoghurt could be resulting from its higher scores in thickness and smoothness according to Kokini’s model of
oral lubrication (Kokini, 1987). Full fat yoghurt also appeared to give more oily coating, as the fat released during oral processing deposited on tongue surface after swallowing.

When adding different hydrocolloids, the sensory attributes of skim yoghurt changed in different manners. Gelatin was the best candidate among the tested hydrocolloids since it improved most of the desirable sensory attributes for yoghurt: thickness, smoothness, creaminess and these attributes were similar to those of full fat yoghurt. This is due to the ability of gelatin to make the yoghurt gel firmer as being shown by its texture, and it distinct characteristic of melting at oral condition which resulted in smooth and creamy mouthfeels. This sensory characteristic of skim gelatin sample is in agreement with its texture, rheological and tribological behaviours observed in sections 3.1 and 3.2. The only attributes that separated the skim gelatin and full fat yoghurt were oily coating and stickiness. Skim gelatin yoghurt has low oily coating due to its much lower fat content compared to full fat yoghurt; and its slightly higher stickiness may be due to the ability of gelatin to interact with casein micelle aggregates and chains of milk proteins (Andić, et al., 2013) which makes the product sticky on oral surfaces.

Adding 0.01% xanthan gum did not change the thickness, but appeared to reduce the smoothness of skim yoghurt. This reduction in smoothness may be the result of the significant increase in undesirable attributes, such as chalkiness, lumpiness and residual coating. The presence of big lumps (seen visually) in sample with added xanthan gum might be due to the depletion flocculation of casein micelles by the xanthan macromolecules to form big particles. This phenomenon has been observed previously using confocal laser scanning microscopy (Hemar, et al., 2001). Carrageenan at the dosage of 0.01% slightly reduced the thickness and substantially increased chalkiness while other sensory attributes are similar to the skim control yoghurt. This slight reduction of thickness of this sample is in agreement with its textural, rheological and tribological behaviors observed in sections 3.1 and 3.2: the slight reduction of yoghurt firmness, viscosity, gel strength and slope of zone 4 in the friction curve.

Adding 1% modified starch slightly reduced smoothness and significantly increased thickness, lumpiness, chalkiness, stickiness and residual coating of skim yoghurt. The increase in thickness of skim yoghurt with added modified starch was in agreement with the increase of the slope of zone 4 ($s_4$) in Figure 8d. This change in sample thickness could not be explained by viscosity at shear rate 50 s$^{-1}$ since there was no significant difference between $\eta_{50}$ for skim yoghurt with and without modified starch (Table 2).
Principle component analysis was performed on sensory scores for six yoghurt samples and the five attributes (thickness, smoothness, lumpiness, stickiness and oily coating) which were best separating the individual samples (Figure 11); the first two principal components accounted for 87.49% of the variability in the results. It is seen that smoothness and lumpiness are negatively correlated which is expected since the presence of lumps reduces smoothness perception. In the first dimension, the smoothness (or less lumpiness) texture increases from skim xanthan, skim starch, skim, skim carrageenan to skim gelatin and full fat (which almost overlap with each other). Attribute vectors for stickiness, thickness and oily coating form the second principle dimension. In term of thickness and stickiness, the six yoghurt samples could be divided into two groups: lower thickness and stickiness (skim carrageenan, skim and skim xanthan) and higher thickness and stickiness (full fat, skim gelatin and skim starch which are similar). Skim gelatin and full fat yoghurt also appear to have higher oily coating than other samples.

To sum up, the principle component display in Figure 11 suggests sensory attributes of the six yoghurts can be described by two texture factors: PC1 (smoothness and the absence of lumpiness) and PC2 (thickness, stickiness and oily coating). We relate these factors with tribology parameters in the next section.

3.4. Relation between tribology and sensory

Relation between syneresis, texture and rheology properties and sensory attributes for the six selected yoghurt samples mentioned above were performed through the correspondence of the ranking of products by PC1 and PC2 and parameters from Table 2, Figures 3 and 4 (firmness, %syneresis, apparent viscosity at 50 s\(^{-1}\), storage and loss moduli at different angular frequencies: 1, 10, 50 and 100 rad/s). However, no correlation between them has been observed. Viscosity at oscillatory frequency of 50 s\(^{-1}\) has been suggested to have a good correlation with perceived thickness, stickiness and sliminess for a wide range of food products from Newtonian fluid to thick emulsion (Shama, et al., 1973; Shama & Sherman, 1973; Wood, 1968). Richardson, Morris, Ross-Murphy, Taylor, and Dea (1989) found better correlation with complex viscosity obtained from the oscillatory small deformation experiments at a frequency of 50 rad/s. However these hypothesis was not supported by many later works (Christensen, 1979; Cutler, Morris, & Taylor, 1983; Kravchuk, Torley, & Stokes, 2012) arguing that food is exposed to a range of shear and deformation processes during oral processing, which lead to its various responses with regards to flow behaviour. Here, in this
work, none of these rheology parameters showed correlation with sensory attributes not only at 50 s\(^{-1}\) or 50 rad/s, but also at many other tested rates.

We then performed similar test by examining the relation between tribological parameters (Table 3) and sensory attributes through the correspondence of the ranking of products by PC1 and PC2 and the tribology attributes. It has been observed that only three tribology parameters \(v_3, s_2\) and \(s_4\) showed correlation with sensory characteristics, the corresponding scatter plots are presented in Figure 12. Excepting for the skim gelatin, \(v_3\) appeared to be in agreement with the ranking by PC1 which describes smoothness - lumpiness sensory attributes (Figure 12a). Since \(v_3\) is the entrainment speed at transition point between zones 3 and 4, it corresponds to the speed at which the hydrodynamic fluid film starts to entrain between the two contact surfaces. Its value could be correlated to sensory texture attributes relating to bulk fluid properties which, in this case, are smoothness and lumpiness.

The slopes \(s_2\) and \(s_4\) show their good agreement with PC2 in Figures 12a and c, respectively. As discussed in section 3.2, zones 2 and 4 correspond to the entrainment of fluid gel in the form of (thin) lubrication film and (thick) hydrodynamic film, respectively. Therefore, it is expected that \(s_2\) correlates to mouth coating (stickiness and oily coating) which are related to thin film properties. The higher value of \(s_2\), the greater the ability of the lubrication film to entrain and adsorb onto the tape surface, whose wettability is similar to human tongue (Nguyen, Nguyen, et al., 2016). This may be the reason why the sample with higher \(s_2\) value (such as skim starch, skim gelatin and full fat yoghurt) tends to give more coating on oral surfaces than others.

Interestingly, \(s_2\) also appeared to correlate to thickness which was believed to relate to bulk fluid viscosity (Kokini, 1987). This correlation suggests that thickness or viscosity of fluid may not only affect its friction behaviour at high speeds (large gap), but also have an impact on the friction of lubrication film at low speeds (narrow gap).

The parameter \(s_4\), on the other hand, correlates to PC2 mainly due to its correlation to thickness attribute (Figures 12c). This observation is expected since it has been popularly known that the friction behaviour of zone 4 (i.e. hydrodynamic regime) is governed by the fluid viscosity (Butt, et al., 2004; Joyner, et al., 2014; Williams, 2005). In this work, we particularly show that the slope of this regime related to the ability of yoghurt gel to entrain into the contact zone and create a hydrodynamic fluid pressure which is sufficient to separate the two contact surfaces (Williams, 2005).
4. Conclusions

We have presented a systematic study on the physical, tribology and sensory characteristics of pot-set yoghurts with different fat contents and with different levels of hydrocolloids. For yoghurt samples with different fat levels (0.1%, 1.3% and 3.8%), the high fat product had firmer texture, less syneresis, weaker gel strength and higher lubrication properties at 35 °C. Among the four hydrocolloids investigated, gelatin appears to be the best stabilizer for skim yoghurt (0.1% fat) because of its ability to significantly improve product firmness, reduce syneresis, lubricity and improved sensory perception of skim yoghurt toward full fat yoghurt. Modified starch increased the thickness of the sample but also created other undesirable mouthfeel attributes, such as chalkiness and lumpiness. Adding carrageenan and xanthan gum improved the sample viscosity and gel strength at a very low dosage, but also resulted in an increase in syneresis and reduced gel stability at high shear rates in tribology measurement. These hydrocolloids also increased product chalkiness and lumpiness, which may be due to the depletion flocculation of casein micelle.

A tribology model with four friction zones has been suggested for tribology measurement using ring-on-plate tribo-rheometry and Transpore Surgical Tape as the tongue model. The lubrication characteristics of the fluid in each zone can be represented by the entrainment speed and friction coefficient at each transition point and the slope of each zone. Three tribology parameters show correlations with the first principle components of selected sensory: the speed at the beginning of the last tribology zone (zone 4), in which the behavior of the fluid depends on the rheology and gel strength, correlates with (smoothness and lumpiness); and the slopes of the friction curve (which shows relation between friction coefficient and entrainment speed) in zones 2 and 4, correlate with (thickness, stickiness and oily coating). It should be noted that this model is valid for yoghurt and other dairy products having a gel structure (such as milk gel). Similar model for liquid dairy is under development.

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Legends of figures

Figure 1. Viscosity of yoghurt samples of different fat levels at different shear rates.

Figure 2. Viscosity profile of skim yoghurt with different levels of fat replacers: (a) gelatin, (b) xanthan gum, (c) carrageenan and (d) modified starch.

Figure 3. Storage modulus $G'$ (black symbols), loss modulus $G''$ (white symbols) and tan $\delta$ (grey symbols) as a function of frequency for pot-set yoghurts with various fat contents (strain 0.01%). The symbols for skim (0.1% fat), trim (1.3% fat) and full fat (3.8% fat) samples are presented in diamond, circle and triangular symbols, respectively. The shaded areas represent standard deviation of three replicates.

Figure 4. Storage modulus $G'$ (black symbols), loss modulus $G''$ (white symbols) and tan $\delta$ (grey symbols) as a function of frequency for pot-set yoghurts for skim yoghurt (0.1% fat) with different levels of fat replacers: (a) gelatin; (b) xanthan gum; (c) carrageenan and (d) modified starch. The shaded areas represent standard deviation of three replicates.

Figure 5. Schematic diagram of four zones in the friction curve.

Figure 6. Tribological data for pot-set yoghurt of different fat levels: skim (circle symbols), trim (square symbols) and full fat (triangle symbols). The friction curve for dry contact (no sample between the contact surfaces) and distilled water were also presented for references.

Figure 7. Confocal laser scanning microscope images of liquid whey from (a) skim yoghurt, (b) trim yoghurt and (c) full fat yoghurt.

Figure 8. Tribological data for skim yoghurt (0.1% fat) with different levels of fat replacers: (a) gelatin; (b) xanthan gum; (c) carrageenan and (d) modified starch. The error bars represent standard deviation of three replicates.

Figure 9. Tribological data for skim yoghurt (0.1% fat) with different levels of xanthan gum as a function of combined parameter of effective viscosity (Pa.s) and entrainment speed (mm/s). The error bars represent standard deviation of three replicates.

Figure 10. Sensory results from Quantitative Descriptive Analysis from 6 pot-set yoghurt treatments: full fat, skim, skim gelatin, skim carrageenan, skim xanthan gum, and skim modified starch yoghurt in 8 major attributes. Standard errors of means for each attribute are: smoothness (0.32), thickness (0.18), lumpiness (0.23), residual coating (0.16), oily coating (0.15), chalkiness (0.23), stickiness (0.22), and creaminess (0.23).
Figure 11. Principal component analysis on the sensory scores for 6 pot-set yoghurt treatments: full fat, skim, skim gelatin, skim carrageenan, skim xanthan gum, and skim modified starch yoghurt.

Figure 12. Relation between tribology parameters ($v_3$, $s_2$ and $s_d$) and principle component (PC1 and PC2) of sensory scores of the six yoghurt samples
Highlights

- Different fat replacers have diverse effects on the lubrication properties of yoghurt
- Gelatin best improves the physical, tribology and sensory characteristics for yoghurt
- We suggest a four-zone model to describe tribology behaviours for pot-set yoghurt
- Tribology provides a better tool to predict the mouthfeel sensory than other methods
The graph illustrates the relationship between the log friction coefficient and log entrainment speed, with four distinct zones:

- **Zone 1**: Fluid whey entrainment ($T_1(v_1, f_1)$).
- **Zone 2**: Local maximum friction ($T_2(v_2, f_2)$).
- **Zone 3**: Fluid gel entrainment (thick film developing) ($T_3(v_3, f_3)$).
- **Zone 4**: Fluid gel entrainment (Hydrodynamic film) and Gel structural breakdown ($T_4(v_4, f_4)$).

The graph shows an increase in film thickness/gap as the log entrainment speed increases.
Table 1. Definitions of the textural attributes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>Resistance to flow in the mouth before saliva modifies the sample</td>
</tr>
<tr>
<td>Smoothness</td>
<td>Perceived smoothness of the sample squeezed between palate and tongue</td>
</tr>
<tr>
<td>Creaminess</td>
<td>Silky smooth sensation in the mouth</td>
</tr>
<tr>
<td>Powderiness/Chalkiness</td>
<td>Powdery sensation</td>
</tr>
<tr>
<td>Stickiness</td>
<td>Degree to which the sample sticks to the teeth and palate</td>
</tr>
<tr>
<td>Lumpiness</td>
<td>Amount of soft lumps or graininess present in the sample</td>
</tr>
<tr>
<td>Oily coating</td>
<td>Oily coating in the mouth after swallowing</td>
</tr>
<tr>
<td>Residual coating</td>
<td>Intensity of residues left in the mouth after swallowing</td>
</tr>
</tbody>
</table>
Table 2. Firmness (N), syneresis (%) and viscosity $\eta_{50}$ (Pa.s) of the pot-set products. The data presented is the average of three replicates with standard deviation.

<table>
<thead>
<tr>
<th>Product</th>
<th>Firmness (N)</th>
<th>Syneresis (%)</th>
<th>Viscosity $\eta_{50}$ (Pa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full fat (3.8% fat; 3.6% protein)</td>
<td>0.31 ± 0.01$^b$</td>
<td>7.44 ± 0.75$^b$</td>
<td>0.35 ± 0.11$^a$</td>
</tr>
<tr>
<td>Trim (1.3% fat; 3.5% protein)</td>
<td>0.18 ± 0.01$^a$</td>
<td>13.77 ± 0.55$^a$</td>
<td>0.20 ± 0.07$^a$</td>
</tr>
<tr>
<td>Skim (0.1% fat; 3.9% protein)</td>
<td>0.22 ± 0.06$^a$</td>
<td>14.77 ± 1.31$^a$</td>
<td>0.71 ± 0.44$^a$</td>
</tr>
<tr>
<td>Skim + 0.5% gelatin</td>
<td>0.35 ± 0.00$^a$</td>
<td>3.00 ± 0.16$^b$</td>
<td>0.29 ± 0.04$^b$</td>
</tr>
<tr>
<td>Skim + 1.0% gelatin</td>
<td>0.62 ± 0.03$^b$</td>
<td>0.17 ± 0.18$^c$</td>
<td>0.31 ± 0.01$^b$</td>
</tr>
<tr>
<td>Skim + 1.5% gelatin</td>
<td>0.93 ± 0.13$^c$</td>
<td>0.05 ± 0.03$^c$</td>
<td>0.21 ± 0.05$^b$</td>
</tr>
<tr>
<td>Skim + 0.005% xanthan gum</td>
<td>0.28 ± 0.07$^a$</td>
<td>18.28 ± 0.72$^b$</td>
<td>1.50 ± 0.63$^b$</td>
</tr>
<tr>
<td>Skim + 0.010% xanthan gum</td>
<td>0.32 ± 0.07$^a$</td>
<td>33.93 ± 1.63$^c$</td>
<td>2.79 ± 1.63$^ab$</td>
</tr>
<tr>
<td>Skim + 0.015% xanthan gum</td>
<td>0.48 ± 0.08$^b$</td>
<td>41.51 ± 1.99$^d$</td>
<td>4.35 ± 2.91$^b$</td>
</tr>
<tr>
<td>Skim + 0.01% carrageenan</td>
<td>0.25 ± 0.03$^a$</td>
<td>23.03 ± 2.12$^b$</td>
<td>0.87 ± 0.92$^a$</td>
</tr>
<tr>
<td>Skim + 0.04% carrageenan</td>
<td>0.27 ± 0.01$^a$</td>
<td>33.62 ± 3.52$^c$</td>
<td>1.21 ± 0.66$^a$</td>
</tr>
<tr>
<td>Skim + 0.08% carrageenan</td>
<td>0.72 ± 0.13$^b$</td>
<td>42.88 ± 4.71$^d$</td>
<td>3.54 ± 1.15$^b$</td>
</tr>
<tr>
<td>Skim + 0.5% modified starch</td>
<td>0.33 ± 0.00$^b$</td>
<td>16.99 ± 0.91$^a$</td>
<td>0.56 ± 0.30$^b$</td>
</tr>
<tr>
<td>Skim + 1.0% modified starch</td>
<td>0.41 ± 0.01$^b$</td>
<td>11.26 ± 0.66$^c$</td>
<td>0.72 ± 0.10$^a$</td>
</tr>
<tr>
<td>Skim + 1.5% modified starch</td>
<td>0.38 ± 0.00$^b$</td>
<td>12.70 ± 0.14$^b$</td>
<td>0.82 ± 0.22$^a$</td>
</tr>
</tbody>
</table>

$^a$ Mean value is significantly different compared to skim yoghurt ($P<0.05$).
$^b$ Mean values in the same group sharing the same letter are not significantly different ($P<0.05$).
Table 3. Parameters obtained from tribology model for pot-set yoghurts. The data presented is the average ± standard deviation of three replicates.

<table>
<thead>
<tr>
<th></th>
<th>$v_1$</th>
<th>$f_1$</th>
<th>$v_2$</th>
<th>$f_2$</th>
<th>$v_3$</th>
<th>$f_3$</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$s_3$</th>
<th>$s_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full fat (3.8% fat)</td>
<td>0.12 ±0.02</td>
<td>0.13 ± 0.01</td>
<td>2.21 ±0.49</td>
<td>0.18 ± 0.00</td>
<td>22.51 ±0.00</td>
<td>0.14 ± 0.00</td>
<td>-0.054 ±0.006</td>
<td>0.209 ± 0.007</td>
<td>-0.192 ± 0.004</td>
<td>0.153 ± 0.016</td>
</tr>
<tr>
<td>Trim (1.3% fat)</td>
<td>0.03 ± 0.00</td>
<td>0.16 ± 0.01</td>
<td>1.28 ±0.08</td>
<td>0.21 ± 0.00</td>
<td>23.41 ±1.56</td>
<td>0.14 ± 0.00</td>
<td>-0.033 ±0.012</td>
<td>0.111 ± 0.014</td>
<td>-0.195 ± 0.012</td>
<td>0.122 ± 0.025</td>
</tr>
<tr>
<td>Skim (0.1% fat)</td>
<td>-</td>
<td>-</td>
<td>0.29 ±0.13</td>
<td>0.43 ± 0.00</td>
<td>11.15 ± 1.87</td>
<td>0.39 ± 0.00</td>
<td>-</td>
<td>0.087 ± 0.022</td>
<td>-0.025 ± 0.004</td>
<td>-0.050 ± 0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.28 ±0.10</td>
<td>0.42 ± 0.00</td>
<td>2.45 ±0.31</td>
<td>0.40 ± 0.00</td>
<td>-</td>
<td>0.066 ± 0.020</td>
<td>-0.030 ± 0.008</td>
<td>0.013 ± 0.006</td>
</tr>
<tr>
<td>Skim + 0.5% gelatin</td>
<td>-</td>
<td>-</td>
<td>0.35 ±0.14</td>
<td>0.41 ± 0.00</td>
<td>2.18 ±0.14</td>
<td>0.39 ± 0.00</td>
<td>-</td>
<td>0.070 ± 0.009</td>
<td>-0.022 ± 0.002</td>
<td>0.020 ± 0.003</td>
</tr>
<tr>
<td>Skim + 1.0% gelatin</td>
<td>-</td>
<td>-</td>
<td>0.33 ±0.11</td>
<td>0.41 ± 0.00</td>
<td>1.56 ±0.19</td>
<td>0.40 ± 0.00</td>
<td>-</td>
<td>0.081 ± 0.007</td>
<td>-0.015 ± 0.010</td>
<td>0.028 ± 0.005</td>
</tr>
<tr>
<td>Skim + 1.5% gelatin</td>
<td>-</td>
<td>-</td>
<td>0.15 ±0.09</td>
<td>0.41 ± 0.00</td>
<td>3.31 ±0.53</td>
<td>0.39 ± 0.00</td>
<td>-</td>
<td>0.123 ± 0.031</td>
<td>-0.019 ± 0.007</td>
<td>0.014 ± 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.11 ±0.02</td>
<td>0.43 ± 0.00</td>
<td>1.92 ±0.60</td>
<td>0.39 ± 0.00</td>
<td>-</td>
<td>0.092 ± 0.014</td>
<td>-0.031 ± 0.014</td>
<td>0.014 ± 0.010</td>
</tr>
<tr>
<td>Skim + 0.005% xanthan</td>
<td>-</td>
<td>-</td>
<td>0.10 ±0.00</td>
<td>0.43 ± 0.00</td>
<td>4.90 ±0.39</td>
<td>0.39 ± 0.00</td>
<td>-</td>
<td>0.046 ± 0.033</td>
<td>-0.012 ± 0.003</td>
<td>-0.022 ± 0.007</td>
</tr>
<tr>
<td>Skim + 0.010% xanthan</td>
<td>-</td>
<td>-</td>
<td>0.22 ±0.00</td>
<td>0.42 ± 0.00</td>
<td>10.20 ±0.00</td>
<td>0.37 ± 0.00</td>
<td>-</td>
<td>0.053 ± 0.020</td>
<td>-0.026 ± 0.003</td>
<td>-0.041 ± 0.001</td>
</tr>
<tr>
<td>Skim + 0.015% xanthan</td>
<td>-</td>
<td>-</td>
<td>0.19 ±0.05</td>
<td>0.44 ± 0.00</td>
<td>54.70 ±21.29</td>
<td>0.32 ± 0.02</td>
<td>-</td>
<td>0.091 ± 0.018</td>
<td>-0.047 ± 0.003</td>
<td>-0.082 ± 0.010</td>
</tr>
<tr>
<td>Skim + 0.01% carrageenan</td>
<td>-</td>
<td>-</td>
<td>0.22 ±0.00</td>
<td>0.44 ± 0.01</td>
<td>10.81 ±0.87</td>
<td>0.37 ± 0.00</td>
<td>-</td>
<td>0.073 ± 0.008</td>
<td>-0.038 ± 0.010</td>
<td>-0.069 ± 0.029</td>
</tr>
<tr>
<td>Skim + 0.04% carrageenan</td>
<td>-</td>
<td>-</td>
<td>0.20 ±0.03</td>
<td>0.44 ± 0.00</td>
<td>2.10 ±0.24</td>
<td>0.40 ± 0.00</td>
<td>-</td>
<td>0.072 ± 0.010</td>
<td>-0.045 ± 0.012</td>
<td>0.015 ± 0.003</td>
</tr>
<tr>
<td>Skim + 0.08% carrageenan</td>
<td>-</td>
<td>-</td>
<td>0.28 ±0.12</td>
<td>0.42 ± 0.00</td>
<td>1.83 ±0.45</td>
<td>0.39 ± 0.01</td>
<td>-</td>
<td>0.243 ± 0.110</td>
<td>-0.048 ± 0.009</td>
<td>0.048 ± 0.001</td>
</tr>
<tr>
<td>Skim + 0.5% starch</td>
<td>-</td>
<td>-</td>
<td>0.29 ±0.12</td>
<td>0.43 ± 0.01</td>
<td>1.64 ±0.39</td>
<td>0.40 ± 0.01</td>
<td>-</td>
<td>0.366 ± 0.063</td>
<td>-0.048 ± 0.020</td>
<td>0.049 ± 0.010</td>
</tr>
<tr>
<td>Skim + 1.0% starch</td>
<td>-</td>
<td>-</td>
<td>0.28 ±0.12</td>
<td>0.42 ± 0.00</td>
<td>1.83 ±0.45</td>
<td>0.39 ± 0.01</td>
<td>-</td>
<td>0.243 ± 0.110</td>
<td>-0.048 ± 0.009</td>
<td>0.048 ± 0.001</td>
</tr>
<tr>
<td>Skim + 1.5% starch</td>
<td>-</td>
<td>-</td>
<td>0.29 ±0.12</td>
<td>0.43 ± 0.01</td>
<td>1.64 ±0.39</td>
<td>0.40 ± 0.01</td>
<td>-</td>
<td>0.366 ± 0.063</td>
<td>-0.048 ± 0.020</td>
<td>0.049 ± 0.010</td>
</tr>
</tbody>
</table>