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Roles of viscosity, applied load and surface wettability on the lubrication behaviour of model liquid/semi-solid foods: Measurements with a bespoke tribo-cell fixture and rotational rheometer

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ABSTRACT

Thin film sliding and friction phenomena of food bolus confined between tongue-palate surfaces during oral processing can be explored using tribological measurements. However, these measurements are still limited within the food industry due to the requirement of expensive commercial instruments which are not commonly used in the food industry. This work has designed and manufactured a modular "tribological cell" (tribo-cell) that can simulate lubricated soft-hard contact interfaces and can be mounted on a rotational rheometer to perform tribological measurements. The tribo-cell was validated by performing tribological measurements using a range of corn syrup solutions as model liquid foods. It was shown that the Stribeck curve describing the change in friction behaviour with entrainment speed or with the product of entrainment speed and liquid viscosity could be obtained. Since tribology deals with surface property, the cell was then used in the further studies to demonstrate the effects of applied normal load and surface wetting on the tribological response of lubricated hard-soft contact of the designed fixture. These parameters were shown to have a marked influence on in the boundary and mixed-lubrication regimes. The designed tribo-cell was also used to illustrate the impact of fat content on the lubrication properties of commercial liquid and semi-solid foods with different fat contents, thus, pointing out to the importance of tribology as a vital tool for product formulation designs in food and beverage industry.

1. Introduction

In-mouth food processing is a complex process involving oral muscle activities as well as jaws and tongue movements that lead to preparing food bolus to be readily swallowed to the next part of gastrointestinal (GI) track. The fundamental mechanisms of food oral processing include food structural breakdown during the first bite and its subsequent chewing. This is followed by agglomeration of food particles by secreted saliva and formation of food bolus with a microstructure and texture suitable for swallowing (Chen 2009, 2015; Chen and Stokes, 2012; Selway and Stokes, 2014; Witt and Stokes, 2015). By using mechanical, rheological and tribological techniques, the process of disintegrating the whole food to a swallowable bolus can be realised. Furthermore, it has been recognised that texture perception during food oral processing is associated with a combination of bulk and lubricated thin film properties which can be measured using the mentioned techniques (Chen and Stokes, 2012; Stokes et al., 2013).

During in-mouth processing, textural properties that are related to food rheology can be detected quickly, i.e., sensory thickness that is related to viscosity. In contrast, those sensory attributes associated with thin-film or tribological property are usually perceived at much longer time. The thin film-related properties can be perceived as related to those mouthfeel attributes, including creaminess, smoothness, slipperiness, astringency, stickiness (Chen and Stokes, 2012; Witt and Stokes, 2015; Sarkar et al., 2021). Since tribology is related to the study of friction, lubrication, and wear of interaction surfaces in relative motion, the most important parameter in tribological experiment is the coefficient of friction (Williams, 1994). In dry contact, this parameter depends

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only on the properties of the interacting surfaces. On the contrary, under lubricated contact or thin film, such friction parameter can vary significantly with the applied load and fluid properties such as viscosity and wettability (van Aken et al., 2011). In this case, the tribological behaviour is often described by a Stribeck curve, which consists of three lubrication regimes, namely, (i) Boundary lubrication regime where two interacting surfaces are in contact, resulting in high friction coefficient, (ii) Mixed lubrication regime where the two surfaces partially touch each other and the coefficient of friction is diminished, and (iii) Hydrodynamic lubrication regime where the two surfaces completely separate by a thin layer of fluid, leading to lower friction coefficient than the lubrication regime (Stribeck, 1902; Bongaerts et al., 2007).

Studying food oral processing is vital for their formulation development, quality assurance as well as consumer perception of sensory attributes to minimise any chewing and swallowing texture-related complaints from consumers. Particularly, understanding the tribological/lubrication behavior of food products can also assist in redesigning ingredients and formulations with better mouthfeel and sensory performance. The study of food tribology has received much interest from food industry in the last decade as this approach has been shown to be beneficial for evaluating and understanding the perceived oral texture of various food systems (Malone et al., 2003; de Wijk et al., 2006; Chojnicka et al., 2008; van Aken et al., 2011, Stokes et al., 2011; Chen and Stokes, 2012; Prakash et al., 2013; Nguyen et al., 2016; Shewan et al., 2019; Sarkar et al., 2021). It has been shown that tribology is a useful tool for better understanding the relationship between food structure, texture, and sensory properties such as lubricity, creaminess, or mouthfeel. Nonetheless, this subject of research is rather complex and much challenging that it requires a multidisciplinary approach to gain a better understanding on the subject and to perform effective measurements (Witt and Stokes, 2015). For most tribological studies on food systems, the measurements are usually performed using commercial tribometers, such as the simple pin-on-disc or the more advanced mini-traction equipments which are generally expensive and not conveniently accessible in food industry (Rudge et al., 2019). In addition, some custom-designed jigs which can be mounted to a rheometer have also been proposed but this approach is relatively scarce (Kavehpour and McKinley, 2004; Goh et al., 2010; Mills et al., 2013). Although a range of tribological testing geometries are available to purchase, they are often not economical and limited in terms of manipulating a hard-soft contact condition for simulating the actual palate-tongue contact during oral processing. The use of a rheometer to perform tribological tests is also considered advantageously for food industry as many food manufacturers are often set up with such instrument for their product characterisation and quality control process.

In this contribution, a bespoke tribological testing fixture that can be attached to a strain-controlled rheometer was developed to quantify and understand the tribological behavior of liquid and semi-solid foods. The designed jig can accommodate for a soft substrate surface, thus, offering to imitate the hard-soft contact condition between human palate and tongue within the oral cavity. Furthermore, the designed jig was used to study the roles of viscosity, applied load and surface wettability on lubrication property of model liquid foods. Finally, the versatility of the designed jig was demonstrated by performing the tribological tests on liquid and semi-solid foods using milks and mayonnaise samples with different fat contents.

2. Experimental methods

2.1. Materials

Corn syrup (Corn Products Refining, Co.), pasteurised milk (Meiji full-fat with 4 %w/v fat and Meiji zero-fat) and mayonnaise (Hellmann's Real containing 78% rapeseed oil and Hellmann's Light with 25% rapeseed oil) samples were purchased from a local supermarket. For corn syrup solutions, different concentrations between 20 and 100% w/w were prepared by simply diluting with deionised water. A silicon oil and polyethylene glycol (PEG, Mw = 200 Da) were purchased from Sigma Aldrich (USA). RTV silicone rubber (KE17) and the curing agent (CAT-RM) used for preparing a soft substrate to simulate the tongue surface were acquired from ShinEtsu silicone (Japan).

2.2. Design and manufacture of a tribological cell

A "tribological cell" (Tribo-cell) was designed and manufactured in-house for tribological measurements as shown in Fig. 1. The geometry was customised such that it could be mounted on a rotational strain-controlled rheometer (ARES-G2, TA Instruments). For this design, the tongue-palate contact for mimicking oral processing was simulated by two hemisphere stainless steel balls and a silicone substrate. This ball-on-disk design has mostly been used in the study of food oral processing (Goh et al., 2010; Prakash et al., 2013; Sarkar and Krop, 2019). These balls were Computer Numerical Control (CNC)-machined and have a radius (R) of 9.5 mm. They can be securely attached to a single rigid arm, which, in turn, is attached to the rheometer shaft consisting of a load coupling unit (see Fig. 1(b)). The coupling unit is essential to ensure good alignment between the contacting surfaces. The normal load was balanced on two contact points between the balls and the silicone substrate at equal distance from the center of the rheometer shaft. In particular, the contact with the hemispheres was at a distance (l) of 22 mm from the center of the shaft and 7.25 mm from the inner surface of specimen cup in which the silicone substrate was mounted on. The silicone substrate was housed tightly in a stainless steel cup and mechanically fastened by a bolt, located centrally of the cup, to secure in place rigidly. This means no testing liquid can be leaked underneath the substrate during measurement. The cup was mounted onto the base of the rheometer containing a peltier system. This bespoke design is flexible and can potentially accommodate various substrate materials and contacting geometries. As suggested by Goh and co-workers (Goh et al., 2010), the use of a two-contact system effectively prevented the application of a bending moment on the bearings of the rheometer and the pivot also allowed equal application of the normal force on the contact points, thus providing smooth rotation during tribological measurements.

To prepare the silicone substrate, the modified method of Ishihara et al. (2013) for preparation of artificial tongue was followed. KE17 silicone was mixed with a curing agent (CAT-RM) at the weight ratio of 100:0.5 and stirred until well combined. The sample was then placed in a vacuum chamber to remove air bubbles before pouring into an in-house designed disk-shape mould with a thickness of 5 mm and a diameter of 64 mm. The mould was sealed, pressed and the sample was kept in the mould to cure at room temperature for about 24 h. Finally, the silicone disk substrate was removed from the mould and surface cleaned with acetone before use. It is worth noting that the stiffness of the silicone can be tailored by simply diluting the formulation with a

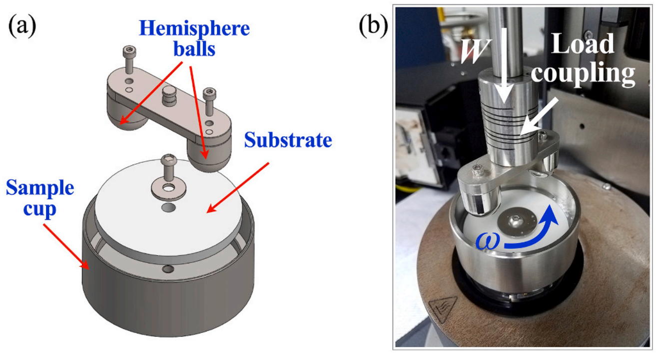

Fig. 1. (a) A schematic drawing of tribological-cell (tribo-cell) and (b) its set-up on a controlled strain rheometer ARES-G2 (TA Instruments, USA).

thinner.

2.3. Rheological measurements

Rheological experiments were performed on selected model liquid and semi-solid foods, i.e., corn syrup solution and commercial food products, using a controlled-strain rheometer (ARES-G2, TA Instruments, USA). The instrument was equipped with either a concentric cylinder or a 40 mm diameter sandblasted parallel plate. The concentric cylinder is of a bob-and-cup type; the height and diameter of the bob are 42 and 27.7 mm, respectively, cup diameter is 30 mm and gap height of 5.917 mm. This geometry was used for measuring low viscosity corn syrup samples. The gap height of 1 mm was used for the parallel plates which were used for testing high viscosity and semi-solid food samples. Dynamic oscillatory experiments were performed using stress sweep measurements from 0.1 to 100 Pa at a constant frequency of 1 Hz and frequency sweep tests between 0.01 and 10 Hz at a fixed stress within the linear viscoelastic range. Furthermore, steady shear experiments were carried out at shear rates between 0.01 and 100 s^{-1}. All measurements were performed at 25.0 ± 0.5 °C. Triplicate runs were performed for each sample and the results shown are the average of all replicates.

2.4. Contact angle measurements

Wettability of model liquid foods on the silicone substrate was examined using contact angle measurements. A video-based optical contact angle system (OCA40 micro, DataPhysics instruments GmbH, Germany) was used to quantify surface wettability of all studied liquid samples. To measure the liquid contact angle, the sessile drop method, that determines the advancing contact angle in a few seconds from the moment the liquid drop is brought into contact with the surface, was used. Using a computer-controlled stage, a small droplet of fluid with approximately 4–6 μL volume was gently displaced from a syringe onto the surface of a silicone substrate used in the tribological measurement. The side view photograph of each droplet was taken and subsequently analysed for the contact angle (θ). All tests were performed under atmospheric conditions and at 25.0 ± 1.0 °C. At least three replicates were used for each liquid sample.

2.5. Tribological measurements

All tribological measurements were performed using the Tribo-cell mounted to a rotational rheometer (ARES-G2, strain-controlled rheometer, TA Instrument, Newcastle, USA). The tribo-cell geometry consists of two hemisphere balls of 9.5 mm in radius (R) and a cup housing a silicone substrate. The cup is attached to a bottom plate adaptor which is secured to the rotating base using a simple bayonet-style locking ring. The two balls are fixed and rigid and only the cup rotates during the measurement (see Fig. 1(b)). The contact between these balls and silicone substrate is assumed to simulate the hard-soft contact between human tongue and palate. To perform the measurement, liquid sample was loaded into the cup; approximately 8 mL of sample was used to ensure that it sufficiently covered the surface of the silicone substrate. The upper hemisphere balls were then lowered onto the substrate until the prescribed normal load was achieved. A range of normal loads varying between 1 and 10 N were used in this study. A pre-condition was prescribed by rotating the cup at an arbitary shear rate of 1 s^{-1} for 60 s while adding testing sample to the cup. This was followed by another 60 s equilibrium time. The speed (ω) ramp in the range of 0.05–350 rpm was then applied to perform the measurement. During the test, the angular speed (ω, in rad/s), torque (T, in N.m) and normal load (W, in N) were measured. Subsequently, sliding speed (V, in mm/s), friction force (F_{friction}, in N) and coefficient of friction (μ) can be calculated from Eqs. (1)–(3), respectively.

$$V = \omega l \tag{1}$$

$$F_{friction} = \frac{T}{l} \tag{2}$$

$$\mu = \frac{F_{friction}}{W} \tag{3}$$

where l is the distance from the center of rotating shaft to the center of the hemisphere balls which is equal to 22 mm based on the geometry shown in Fig. 1. All tests were performed at ambient temperature 25.0 ± 2.0 °C and at least two replicates were used for each sample.

3. Results and discussion

3.1. Rheological measurements

In order assess and validate the efficiency of the designed tribo-cell, various corn syrup solutions, prepared simply by diluting with water, were used, and their rheological properties were measured. The viscosity measurements on various corn syrup solutions showed that they behaved as a Newtonian fluid as shown in Fig. 2(a). The dependence of the viscosity on the corn syrup concentration is shown in Fig. 2(b), indicating the exponential dependence of the corn syrup viscosity on its concentration. Specifically, this dependence can be described by the following equation; $\eta = \eta_0 e^{\left(a\phi^2+b\phi+c\right)}$, where η is the viscosity of corn syrup, η_0 is the water viscosity (equal to 1 mPas), ϕ is the corn syrup concentration (% w/w) and a, b and c are the constants which have values of 8.375, −2.919 and 2.597, respectively. These results shown here are in good agreement with the work of Goh et al. (2010). In addition, silicone oil and PEG200, that were used as model liquid food in the subsequent tribology study to demonstrate the effect of surface wettability, exhibited Newtonian behavior with the measured viscosities of 1.0 and 0.05 Pa, respectively.

3.2. Tribological measurements

3.2.1. Effect of viscosity

To evaluate the effect of liquid viscosity on its lubrication property, tribological measurements were performed on corn syrup solutions with varying viscosity using a controlled normal load of 3 N. This load magnitude is well below load-applying capability of tongue from able-bodied individuals that has been reported to be capable of applying forces in the range of 13 N (Robinovitch et al., 1991; Sarkar et al., 2021). During experiment, the applied normal load can be monitored. Typical normal load profiles for various samples using corn syrup solutions are illustrated in Fig. 3. It is evident that satisfactory steady normal load could be achieved during the measurement, thus confirming the feasibility and attractiveness of using such set-up with a rotational rheometer to perform tribological tests. Such implementation is considered beneficial for food industry as most food laboratories are often equipped with a rheometer but not necessarily with a tribometer. Fig. 4(a) and (b) show the measurement of Stribeck curves plotted in terms of the coefficient of friction as a function of entrainment speed and the product between corn syrup viscosity and entrainment speed (ηV), respectively, for various corn syrup solutions. It is clearly demonstrated here that the characteristic of Stribeck curve is influenced by the liquid viscosity when plotted as a function of the entrainment speed (Fig. 4(a)). For low viscosity liquid, i.e., using 20% w/w corn syrup, there was no or very little fluid entrainment into the contact such that only the boundary lubrication regime could be observed across the applied rotation speed. As the liquid viscosity was increased, both boundary and mixed lubrication regimes could be measured, indicating that the fluid could be entrained between the contact at higher speed, thus, generating sufficient hydrodynamic lift to partially separate asperity contacts between the two surfaces. At high enough liquid viscosity, i.e., 100% w/w corn syrup, the

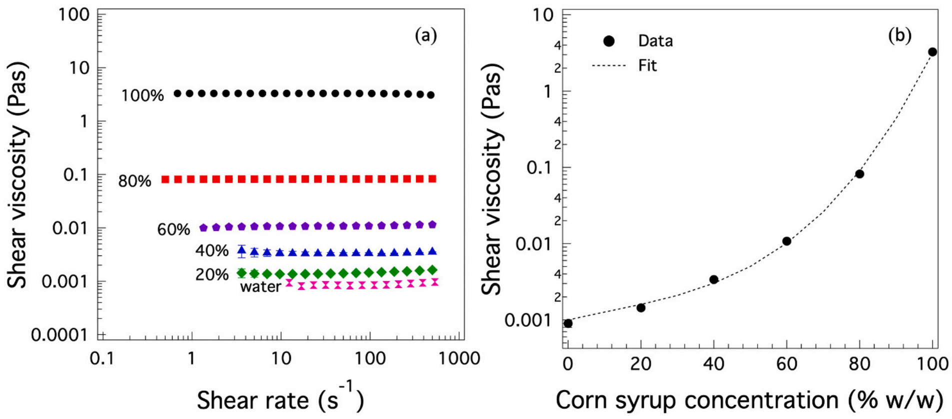

Fig. 2. (a) Newtonian behavior of corn syrup solutions at different concentrations and (b) viscosity of corn syrup solution as a function of its concentration.

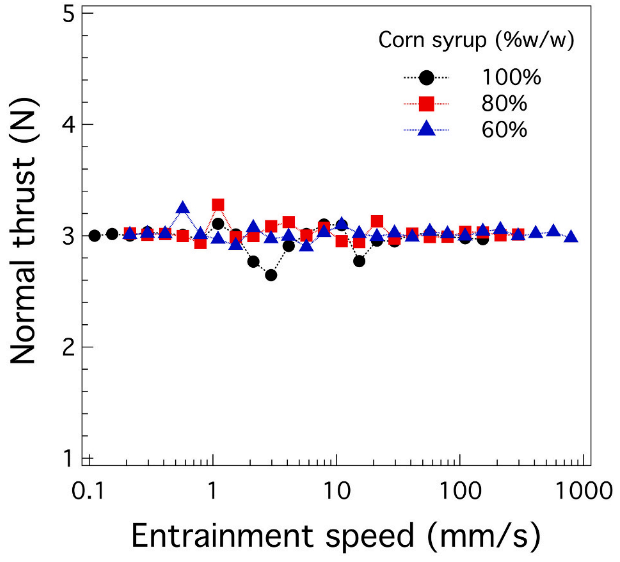

Fig. 3. Measured normal load during tribological measurements with a rotational rheometer on corn syrup solutions at different concentrations.

hydrodynamic lubrication regime could readily be measured even at low entrainment speed, suggesting a full film separation between the surfaces. In this regime, the film thickness increases with increasing speed and friction also increases due to more intense turbulent flow. However, the Stribeck curves could be collapsed to a master curve, showing all three lubrication regimes, when plotted as a function of ηV in Fig. 4(b). This result shows that, for Newtonian liquids, the liquid viscosity is considered as a shift factor for the Stribeck curve, i.e., the higher the viscosity, the shifting is more toward the hydrodynamic lubrication regime. This finding is consistent with many previously published works (de Vicente et al., 2005; Goh et al., 2010; Selway and Stokes, 2013; Shewan et al., 2019).

3.2.2. Effect of normal load

The influence of applied normal load on the tribological properties of corn syrup solutions and water is shown in Fig. 5(a) and (b), respectively. The results are shown in terms of the relationship between the friction coefficient and Sommerfeld number which is the dimensionless number defined as $\eta VR/W$, where R and W are the ball radius and normal load, respectively. This number was initially designed for journal bearing application and has been used frequently in automotive industry (Williams, 1994; Khonsari and Booser, 2010). The resulting Stribeck curve also consists of Boundary, Mixed and Hydrodynamic-lubrication regimes when combining the data using 80% w/w and 100% w/w corn syrup samples. The data is scalable and can be collapsed onto the same master curve in the hydrodynamic lubrication regime. However, there is a loss of scale invariance in the obtained Stribeck curve in which the friction coefficient showed a dependence on the applied load (pressure), especially in the boundary and mixed-lubrication regimes. In these two regimes, the true asperity contact and partial adhesion over the true contact area are dominant factors controlling the friction

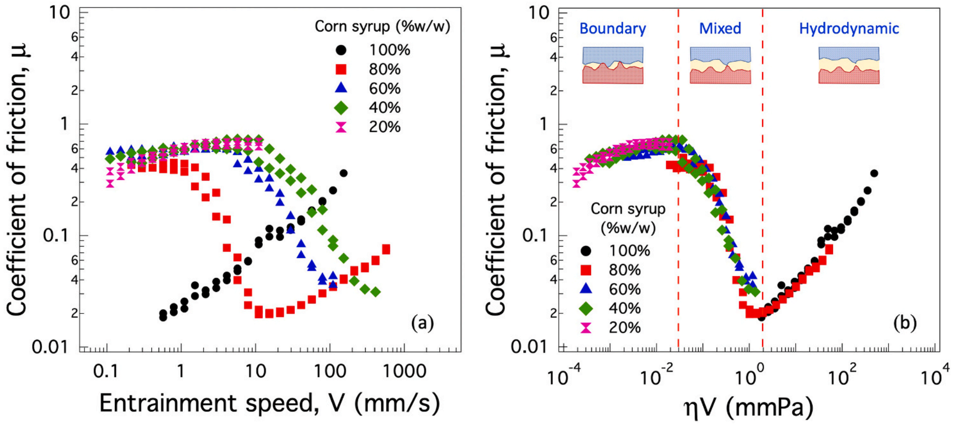

Fig. 4. Tribological properties of model liquids with varying viscosity, plotted as a function of (a) entrainment speed, *V* and (b) *the product between* viscosity and entrainment speed, ηV with the applied normal load of 3 N. Different regions of the Stribeck curve, defined as Boundary-, Mixed- and Hydrodynamic-lubrication regimes are observed and indicated by the *dashed* lines.

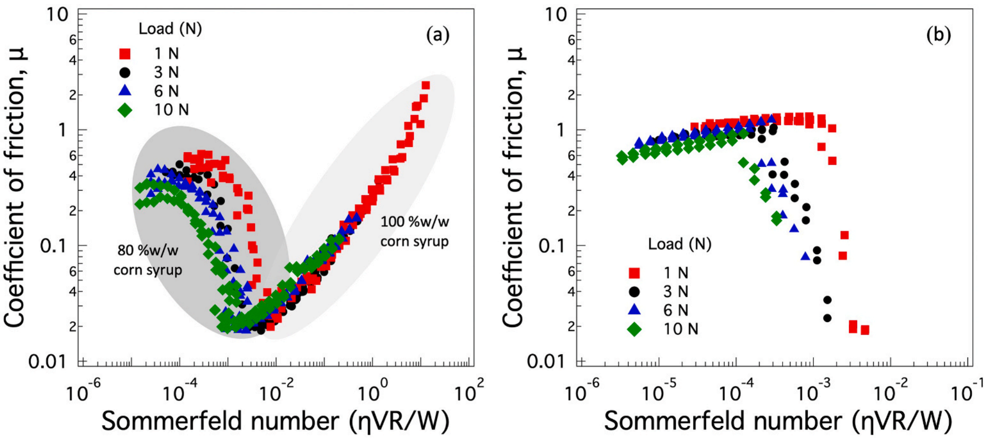

Fig. 5. Effect of applied normal load on the measured Stribeck curves of (a) corn syrup solutions and (b) water.

properties (Denny, 1953). As higher load is applied, asperities are flattened, thus, increasing the real area of contact and diminishing the chance of partial asperity adhesion. As a consequence, friction coefficient is decreased. Similar trends are also observed for the tribological measurements carried out with water using the same load range. However, it was not possible to obtain any data in the hydrodynamic lubrication regime (see Fig. 5(b)). It is also evident here that water is not a good lubricant because of the higher coefficient of friction in the boundary regimes. These findings are in good agreement with past studies by Bongaerts et al. (2007) and Goh et al. (2010). In addition, other previous works have shown that the dependence of friction coefficient on applied load between a lubricated rubber and steel track contact could be described by a linear equation given as $1/\mu = a + b/W$, where a and b are constants (Schallamach, 1952; Denny, 1953; Hua et al., 2017; Sun et al., 2018). This relationship suggests that friction coefficient approaches a constant value when the applied load or pressure is sufficiently high enough that the true asperities contact area eventually reaches a limiting value. However, it is worth pointing out that the use of Sommerfeld number alone is considered inefficient to explain the measured tribological data as it does not adequately capture the change in the contact area as well as the adsorption of liquid molecules on contacting surfaces, especially in those polysaccharide solutions and structurally complex food systems. A more comprehensive review on the influence of adsorbed liquid molecules on the tribological behaviour can be found in the recently published work of Sarkar and co-workers (Sarkar et al., 2021).

3.2.3. *Effect of surface wettability*

To demonstrate the effect of surface wetting on tribological behavior of liquid foods, some Newtonian model fluids, including water, corn syrup solutions, silicon oil and PEG-200 were used. Fig. 6 shows the contact angle measurements of these model liquid foods on a silicone substrate used in the tribological experiment. It was found that water and all corn syrup solutions used in this study showed poor surface wettability and had similar contact angle, e.g., $\theta = 114.1 \pm 5.5°$. Contrarily, silicon oil and PEG-200, which are more hydrophobic, exhibited more superior surface wettability behavior than water and corn syrup solutions, thus, reducing the contact angles to 30.9 ± 4.2° and 83.6 ± 1.8°, respectively (Fig. 6). Tribological behaviour of these model liquids with different surface wetting capability is shown in Fig. 7. The ability of a liquid to wet a surface has a considerable effect on its lubrication property in soft tribology contacts. Specifically, the measured coefficient of friction reduced markedly in the boundary and mixed-lubrication regimes for those liquids with enhanced surface wettability, i.e., silicon oil versus corn syrup solutions. Nonetheless, the coefficient of friction was somewhat unaffected and independent of surface wetting in the hydrodynamic lubrication regime as full film was developed between the contacting surfaces. When comparing corn syrup solutions with water, which showed similar surface wetting characteristics, the effect of surface adsorption by small polymer molecules, i.e., oligosaccharides, in corn syrup solutions on their lubrication behaviour are noticeable. This is evident by the lower coefficient of friction in the boundary lubrication regime compared to that of water. Such distinct tribological characteristics are in good agreement with the previous work by Selway et al. (2017), which explained the decrease in the friction coefficient with increasing fluid wettability by a complex interplay of multiple mechanisms involving dewetting and squeeze-out dynamics of the fluid and the interfacial (viscoelastic) effects occurring between the two contacting surfaces. The effect of wettability on the magnitude of friction coefficient and the transitions between the different lubrication regimes and the mechanism of lubrication has also been discussed in the recent review work of Shewan and co-workers

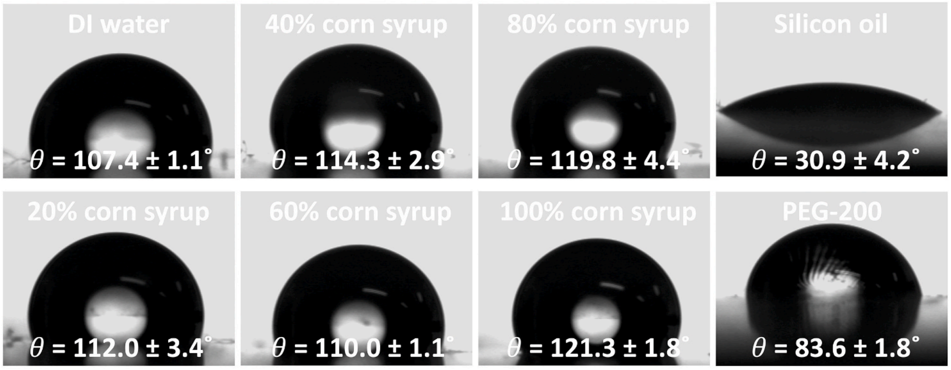

Fig. 6. Surface wettability of model fluids used in this study on a silicone substrate.

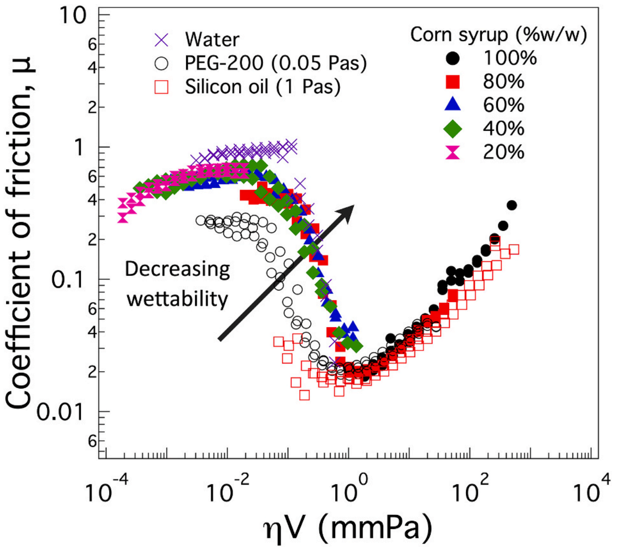

Fig. 7. Tribological properties of some model liquids with different surface wettability, plotted as function of reduced velocity with the applied normal load of 3 N.

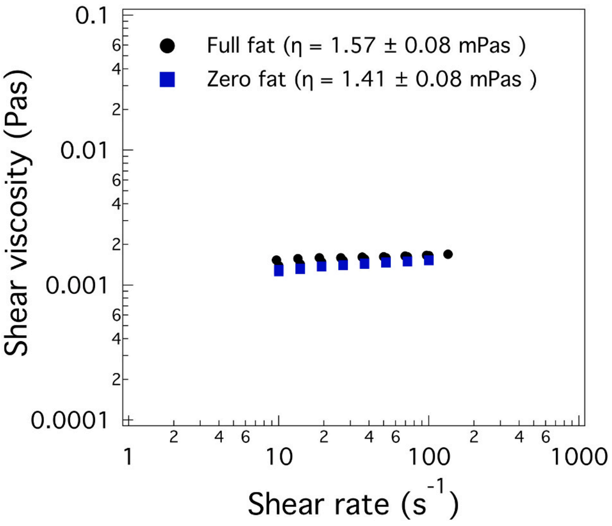

Fig. 8. Comparison of flow properties of full-fat and zero-fat pastuarised milk samples.

(Shewan et al., 2019). For example, the lubrication behaviour by water on hydrophilic PDMS substrate exhibits much lower friction than that on hydrophobic PDMS (Bongaerts et al., 2007).

3.3. *Lubrication properties of liquid and semi-solid foods with varying fat contents*

The results shown above demonstrate that viscosity and wetting properties are important parameters for food product designs. Knowing these properties not only gives food manufacturers the ability to predict how the materials will behave during processing, transportation, and storage, it also helps design food products with controlled texture and mouthfeel to meet the ever-increasing demands from consumers. To demonstrate the usefulness and versatility of tribological measurements for food product designs, further study was carried out on real food system using several commercial food products with varying fat contents, e.g., full-fat and zero-fat milk and real and light mayonnaise samples. Rheological properties of these products are shown in Figs. 8 and 9 for milk and mayonnaise samples, respectively. It is demonstrated here that both products could be tailored to have comparable viscoelastic and flow properties, i.e., similar gel-like viscoelastic behavior, yield stress as well as viscosity, regardless of the fat content. However, tribological measurements on these samples revealed that the full-fat and zero or reduced-fat products still behave somewhat different. The full-fat products showed comparatively lower friction coefficient, hence better lubrication, than those same products with zero or reduced-fat content (Fig. 10). Particularly, the tribological behavior between these full-fat and zero or reduced-fat samples is distinguishable in the mixed- and hydrodynamic-lubrication regimes or at entrainment speeds above 20 mm/s. This is also the region perceived during oral processing and swallowing, suggesting that the mouthfeel properties of these products would be somewhat different. The results shown here are consistent with previous literatures (Prinz et al., 2006; Chojnicka-Paszun et al., 2012; Laguna et al., 2017). For homogenised milk products with varying fat contents, it was shown that the perceived creaminess and friction were significantly altered when the fat content was above 1%. The increased creaminess and thus decreased friction was attributed to the coalescence of fat globules on two interacting surfaces, i.e., surface of the tongue and rubber disc used in their mini traction machine (MTM) set-up (Chojnicka-Paszun et al., 2012). Furthermore, increasing fat content could also prolong constant formation of thin film lubricating layers, that may point to the importance of fat in providing good mouthfeel and creaminess perception (Dresselhuis et al., 2007). Moreover, Prinz et al. (2006) revealed that friction is the major determinant of creaminess attribute of a range of semi-solid foods, including custard and mayonnaise, with different fat contents and the kinetic coefficient of friction, measured with a simple friction apparatus designed by Halling (1976), could vary between 1.2 for zero-fat product to 0.4 for the highest fat product (82%) used in their study. More recently, Laguna et al. (2017) examined the tribological properties of commercial food products such as milk, yogurt and cream cheese with varying fat contents using a commercial MTM tribometer. Their measurements also revealed the similar rheological properties between the same fat-varying product type and concluded that the rheological tests alone were not sufficient to predict the sensory properties of those products. Nonetheless, the tribological behavior of these products were noticeably different with the low-fat sample showing higher friction coefficient compared to the full-fat sample. Thus, they concluded that tribology measurement is a promising technique to better capture the dynamics of oral processing and can be used to unravel insights for texture and mouthfeel perception as perceived by consumers. Similar results were also reported by Selway and Stokes (2013) which showed the different tribological behavior of a range of semi-solid food products containing different fat contents but with similar rheological characteristics, including custard, yogurt. Therefore, the results shown here indicate that there are still shortcomings to address in term of designing healthy food products with similarity in both rheological and tribological or lubrication properties to their conventional counterparts. This present study also confirms that the application of tribology is a vital tool in food product formulation development. It can be used beneficially to provide a broader picture of structure-property-function relationship of food products such that healthy products with improved mouthfeel can be made to meet up with the increasing demand from consumers.

In essence, it is worth pointing out that tribology is a system property and not a fundamental or physical property of a material. Therefore, its measurement is dependent on the system used, i.e. ball on flat, flat-on-flat, characteristics of contact surfaces, i.e. roughness, surface wettability, and the testing materials (types of foods in this case, i.e., liquid, semi-solid or solid foods). The choice of tribology systems is well summarised in the reviews by Sarkar and Krop (2019). Typical tribological measurements have been performed to generate a Stribeck-type curve with a ball-on-disc system, either with sliding-sliding (as similar to this bespoke design) or sliding-rolling configuration. Such system has been shown to correlate well with some sensory attributes such as slipperiness

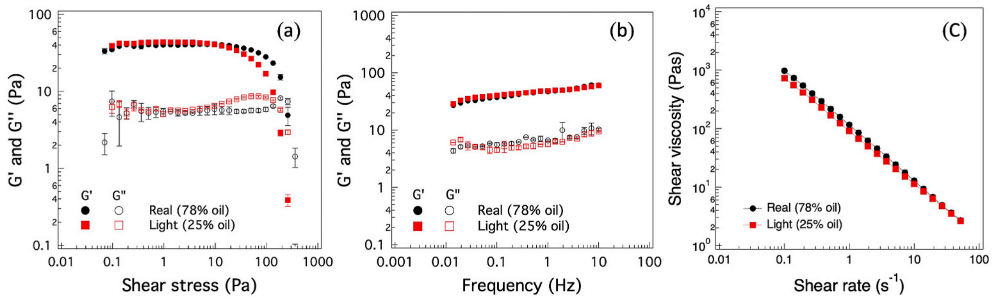

Fig. 9. Comparison of rheological properties of real and light mayonnaise samples obtained from (a) stress sweep (b) frequency sweep and (c) shear rheology measurements.

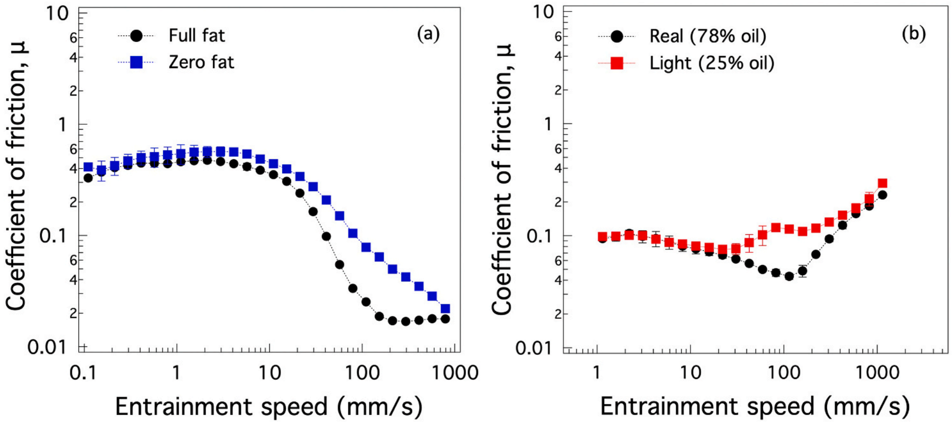

Fig. 10. Comparison of tribological behaviour between (a) full-fat and zero-fat pasteurised milk and (b) full-fat (Real) and light mayonnaise samples, measured with the tribo-cell and applied load of 3 N.

or creaminess in a range of fluid and semi-solid foods (Sarkar and Krop, 2019; Shewan et al., 2019). However, such configuration implies the continued supply of fluids through the inlet that may not capture adequately the mechanism of first bite during food oral processing. For liquids or semi-solid foods, the first bite may not be significant, hence, the ball-on-disc configuration may be efficient to study oral processing for these samples. For solid foods such as chocolate, mechanical breakdown during first bite may contribute to the overall sensory mouthfeel. As a result, other configuration based on flat-on-flat geometry may provide better interpretation of oral processing as proposed in the recent studies by Masen and Cann (2018) and Samaras et al. (2020).

4. Conclusions

A modular tribo-cell fixture that can be attached to a rotational rheometer was designed, machined, and tested for its application in tribology measurement on food products. Successful experiments were carried out using model Newtonian liquids made from corn syrup at varying concentrations to obtain a Stribeck curve. It was shown that liquid viscosity, applied load and liquid wettability have a large influence on the tribological behaviour of lubricated soft-hard contact surfaces. Increasing viscosity shifts the lubrication characteristic toward hydrodynamic lubrication regime, while the data is scalable and collapse to a single Stribeck master curve when plotted in terms of the product between viscosity and entrainment speed (ηV). By varying the applied normal load between 1 and 10 N, the tribological data was only scalable in the hydrodynamic lubrication regime and friction was reduced with increasing applied normal load in the boundary and mixed-lubrication regime as a results of smoother asperity contacts. Enhanced surface wetting also led to lower friction in both the boundary and mixed-lubrication regime. In contrast, it did not affect the tribological response in the hydrodynamic lubrication regime. Further studies on commercial food products using milk and mayonnaise with different fat contents revealed the importance of tribological measurements to improve product formulations development such that both normal fat and reduced/low/zero fat products can exhibit similar bulk rheology as well as tribology, thus providing similar sensory and mouthfeel characteristics. Overall, this work highlights the promise of the designed tribo-cell fixture for probing the lubrication properties of liquid or semi-solid foods. The use of this tool should also assist food manufacturers and scientists to better understand food oral processing and subsequently optimise the formulation design of their interested food products.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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