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Using a three-ball-on-plate configuration for soft tribology applications

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Keywords: friction coefficient, measurement, rheometer, soft tribology.

Abstract

Friction tests are a valuable tool for the analysis of food formulations to understand how they may behave during oral processing. Generally, food laboratories do not own specialist tribological testing equipment. It is more common for them to own or use a rheometer for which most commercially available instruments now offer an attachment to measure friction. The objective of this study was to examine the effect of using a three-ball-on-plate rheometer attachment for soft tribology measurements by assessing the friction properties of various model food-like systems. In addition, results were compared to an existing tribological instrument frequently used in oral processing applications (a mini traction machine) under pure sliding conditions. Results show similarities between the two techniques for simple systems, showing friction results depend less on the specific geometry compared to complex systems. The three-ball-on-plate geometry for the rheometer allowed detailed measurement of the boundary lubrication regime due to achieving low speeds unavailable when using the mini traction machine. Going forward, the three-ball-on-plate tribology attachment will be an incredibly useful tool in oral processing applications.

1. Introduction

Traditionally tribology, the study of friction, lubrication and wear, has been used to determine the properties of systems concerning contacting surfaces like machine components and bearings (Hailing, 1991). More recently, tribology has been used with focus on oral processing to study the frictional properties of food systems, for example oil-in-water emulsions (Chojnicka et al., 2008; Dresselhuis et al., 2007), dairy products (Chojnicka-Paszun et al., 2012; Joyner et al., 2014) and chocolate (Rodrigues et al., 2017). Tribological measurements of foods are generally performed on soft surfaces, such as rubbers, silicones and biological tissues as these more closely resemble oral surfaces than typical steel-steel contacts (Bongaerts et al., 2007; Chen and Stokes, 2012; Dresselhuis et al., 2008; Sarkar et al., 2019). Tribometers, like the Mini-Traction Machine (MTM) by PCS Instruments (Garrec and Norton, 2012; Myant et al., 2010), custom-made laboratory apparatus (de Wijk & Prinz, 2004; Dresselhuis et al., 2008) or rheometers with tribological attachments (Kieserling et al., 2018; Krzeminski et al., 2012) have all been used to understand the tribological properties of foods. Many rheometer manufacturers now offer tribology attachments for their instruments. These systems vary between instrument manufacturers but generally consist of a rotating aspect and a stationary aspect. The contacts can be plates, balls, discs or rings and can consist of two or more contacting surfaces. For example Joyner (Melito) et al. (2014) investigates two tribological apparatus: ball-on-three-plate and double-ball-on-plate. The authors found the tribological measurement system did not affect friction regimes observed for each material, but did affect the magnitude of friction coefficient. The difference in these results were attributed to the set-up of the contacting surfaces as the double-ball system had a horizontal plate; whereas the ball-on-three-plate system had angled plates meaning lubricant flowed off them and measurements were not accurate.

Using a rheometer for tribological applications is advantageous as a range of normal forces, speeds and testing surfaces can be examined with ease suggesting this method can provide similar information to other commercially available tribometers. The advantage of using the rheometer attachment for tribology measurements would be reduced cost and advanced measurement techniques for institutions that own or have use of a rheometer, but cannot warrant the purchase of a specialist piece of equipment for tribology. Rheometer based tribological measurements are relevant for food applications as many food scientists already own a rheometer. In this study, a three-ball-on-plate rheometer attachment is compared to a Mini Traction Machine (MTM), which is well established for use in soft surface tribology. The MTM consists of a disc mounted in a sample pot onto which a ball on a shaft is lowered to be in contact with at a 45° angle. Entrainment occurs between these surfaces as they rotate. Entrainment for the rheometer relies on the mounting plate repelling from the rotating geometry; separating to allow lubricant in between. The plate/disc surface in the rheometer is stationary giving only pure sliding friction measurements, whereas for the MTM a mixture of sliding and rolling friction can be used as both surfaces are able to rotate independently. During oral processing, the tongue moves up and down, pressing the food against the palate in order to process it. Since the palate does not move, it can be assumed that sliding motions likely dominate in the mouth. However, in practice this process is more complex as mastication, saliva incorporation and tongue motion mean food experiences both sliding and rolling motions (Chojnicka et al., 2008).

This study aims to use a range of previously tribologically examined model food systems. These include Newtonian fluids, a shear-thinning hydrocolloid solution, a simple emulsion and a soft particulate system. Hydrocolloids cover a wide range of materials, including a variety of polysaccharides and gums. These are widely used in food formulations as thickeners, rheology modifiers and gelling agents which give structure and specific textural properties to the product (Dickinson, 2003). Guar gum is frequently reported in literature due to its extensive use in foods and Non-Newtonian shear thinning behaviour. Malone previously studied guar gum tribologically finding correlation between concentration and oral perceived slipperiness (Malone et al., 2003). The use of emulsions in food is commonplace; both in manufactured and processed foods, and natural products like milk. Emulsions give textural (for example creaminess, oiliness) and taste to a product. The basic structure of an emulsion consists of two immiscible liquids, typically an oil phase and an aqueous phase. One is dispersed in the form of droplets within the other. Food based emulsions have been well examined tribologically (Anvari and Joyner (Melito), 2017; Douaire et al., 2014; Dresselhuis et al., 2007; Malone et al., 2003). A range of gels are used in food applications where the gelation process leads to a quiescent gel. The gelation process can be modified by applying shear during the cooling process, allowing discrete gel particles to form in suspensions. The resultant material, a fluid gel, is both solid-like and liquid-like. These gels are increasingly being used as fat replacement, due to being able to impart structural properties whilst comprising of mostly water. These show non-typical Stribeck behaviour so will be of interest to compare in this work (Fernández Farrés and Norton, 2015; Gabriele et al., 2010).

The MTM has long been the most widely used instrument in food tribology, however researchers are increasingly using rheometers with tribology attachments to study friction (Pradal and Stokes, 2016). To the author's knowledge, a comparative and evaluative study of rheological apparatus for the application of oral processing has not been performed. Therefore, the objective of this study was to examine the effect of using a three-ball-on-plate rheometer attachment for soft tribology measurements by assessing the magnitude and variation of friction coefficient as well as comparing data to that obtained from the MTM in as close conditions as possible. A range of model food systems were used to compare measurements: Newtonian fluids, a shear-thinning hydrocolloid solution, an oil in water emulsion and a soft particulate fluid gel.

2. Materials and methods

Polydimethylsiloxane (PDMS) (Sylgard 184 Silicone Elastomer kit) was purchased from Dow Corning, US. Guar Gum, Agar and Tween 20 were obtained from Sigma Aldrich, UK. Vegetable oil for use in emulsions was purchased from Sainsbury's, UK. Materials were used with no further modifications or purification.

2.1. Disc preparation

Discs were fabricated using a two-part kit (Sylgard 184) consisting of silicone elastomer and curing agent which were mixed in the manufacturers recommended 10:1 ratio. The binary mixture was poured into a sheet of 4 mm thickness, degassed and placed in an oven at 70 °C for 2 hours. The sheet was left to cool for at least 24 hours and discs were cut out for use in the tribometer using a 46 mm diameter disc cutter. Before all tests, PDMS discs and steel balls were sonically cleaned in isopropanol followed by distilled water for 6 minutes each. They were dried in air and fitted into the tribometer cell. Each disc was used for one experiment and then discarded.

2.2. Guar gum solutions

Samples were prepared by adding the desired concentration (wt%) of guar gum to distilled water and stirring for ~30 minutes. Whilst still stirring, samples were hydrated by heating for a further 30 minutes at 80 °C. In this study, solutions of 0.2%, 0.4% and 0.6% guar were examined. Samples were produced on the same day as testing and tested three times to obtain an average.

2.3. Oil in water emulsions

Oil in water emulsions were prepared using required w/w% of vegetable oil, 1% Tween 20 and distilled water. The samples used in this study contained 20%, 30% and 50% vegetable oil in addition to pure water and pure oil samples. The samples were sheared for three minutes in a Silverson high shear mixer at 10000 rpm. Droplet sizes for all emulsions ranged from 5-10 μm (measured using an optical laser particle size analyser (Mastersizer 2000, Malvern Instruments, UK)). Samples were produced on the same day of testing and tested three times to obtain an average.

2.4. Soft particulate gels

Agar fluid gels were prepared in a lab-scale continuous process pin-stirrer (method replicated from Ellis, Norton, Mills, & Norton (2017)). The required mass of agar was dispersed in deionised water and heated to 90 °C whilst stirring. The resultant hot solution was fed into the jacketed pin-stirrer cooled to 5 °C via a peristaltic pump, set to a speed of 25 mL min^{-1}. The inlet temperature was controlled to ~ 70 °C and the outlet to 5 °C to ensure gelation occurred under shear (gelation temperatures ~ 30 °C). The shaft rotation speed was set to 2000 rpm. Fluid gels were tested after 48 hours to ensure post-production particle ordering completion and stored at 5 °C until use. Particle sizes were measured using an optical laser particle size analyser (Mastersizer, Malvern Instruments, UK). Agar fluid gels of concentration 1%, 2%, 3% and 4% agar were found to have average particle diameters of 188 ± 11 μm, 132 ± 9 μm, 112 ± 14 μm and 125 ± 5 μm respectively.

2.5. Shear rheology

Rheological measurements were performed using a Kinexus Pro rheometer (Malvern Instruments, UK). For the agar fluid gels, viscosity curves were obtained by recording shear viscosity through a range of applied shear rates at equilibrium (0.001–500 s^{-1}). Measurements were performed at room temperature (25°C). To avoid slip a serrated parallel plate geometry was used (60 mm serrated parallel plate) with 1 mm gap. Experiments were carried out in three replicates.

2.6. Tribology

Two different tribological set ups were investigated and compared. A rheometer with three-ball-on-plate tribo-geometry attached and a mini traction machine were used to determine friction properties. A tribo-pair of stainless steel ball and lab-made PDMS discs were investigated; materials previously used to represent of oral surfaces due to similar mechanical properties to that of the tongue (Bongaerts et al., 2007; Dresselhuis et al., 2007). The stainless steel balls were provided by the manufacturer of the instrument used.

2.6.1. Mini-traction machine

A mini traction machine (MTM) manufactured by PCS Instruments, UK was used to perform tribological measurements to compare data obtained from the rheometers. The MTM consists of a ball loaded onto a disc producing a small point of contact where material can be assessed. The ball and disc are independently driven which gives precise control over speeds and direction of rotation of the contacting surfaces as well as ratio of speeds of the contacts. The MTM also allows for control over applied normal force. As the rheometer only has sliding functionality, pure sliding conditions of 200% slide-roll-ratio (SRR) was used. Three tests of ascending sliding speed 1 to 1000 mm/s were completed and the average reported. A volume reducing insert was used allowing for a sample size of 15 mL. Experiments were performed at room temperature (25°C). A normal force of 1 N was used (unless stated otherwise) as in mouth friction was reported to be between 0.1 N and 10 N (Miller and Watkin, 1996). 1 N would allow low contact pressure, which is of relevance in oral processing applications.

2.6.2. Tribology attachment for rheometer

A three ball-on-plate tribology attachment (TA) for Discovery HR-2 rheometer by TA Instruments, UK was used. The geometry consists of 3 x ¼ inch diameter stainless steel hemispheres, which screw onto a flat plate (*Figure 1*). The geometry head where the hemispheres were attached is flexible due to a spring-like beam coupling.

The torque was the independent variable which enabled calculation of friction coefficient. The friction coefficient, μ, was calculated by:

$$\mu = \frac{M}{dF_N}$$

where M = torque (Nm), d = arm length at 0.015 m and F_N = normal force (N).

Flow sweeps were performed measuring torque through a range of applied velocities at equilibrium (0.0001 to 10 radians/s where the linear speed equates to ~ 0.002 to 150 mm/s sliding speed) with ten measurements per decade (50 measurements total) at room temperature (25 °C) and normal force of 1 N, unless stated otherwise. During testing, the PDMS disc was secured using a custom 3-D printed base plate seen in *Figure 2* and visible in *Figure 1*. A sample volume of 15 mL was used. Each sample was tested three times and an average obtained.

The contact area and average contact pressure at 1 N normal force were calculated for both systems and are displayed in *Table 1* below where total contact area was calculated using equations from Gabriele (2011). The TA system has a smaller contact area, but a larger contact pressure when comparing the same applied normal force.

Table 1 – The ball diameter, contact area and average contact pressure at 1 N for the stainless steel ball and PDMS tribo-pair for each tribological set up.

Instrument	Ball diameter (radius, m)	Total contact area 1 N (m^2)	Avg contact pressure 1 N (kPa)
MTM	¾ inch (0.0095)	5.4×10^{-6}	185

TA	¼ inch (0.003175)	3.7 x 10^{-6}	270

3. Results and discussion

A series of Stribeck curves were investigated to compare and evaluate the tribological systems with different test samples: Newtonian fluids (vegetable oil and water), shear thinning polymer solutions of varying guar concentration, oil in water emulsions with varying oil concentration and particulate suspensions (agar fluid gels) with varying agar concentration are reported. These samples were chosen as they cover a range of formulations found in food products. They have also been well investigated tribologically and will be used to allow for comparison between data collected in this study and existing data from literature.

3.1. Newtonian fluids

The tribological behaviour of a Newtonian fluid, vegetable oil, was examined and shown in *Figure 3* comparing the MTM and tribology attachment (TA) for rheometer measurement systems. The TA system showed typical Newtonian behaviour, with a full Stribeck constructed over the speed range tested. Above 1 mm/s, the MTM and TA systems show similar behaviour to one another. For the MTM, it is clear only the hydrodynamic regime is present under these testing conditions as friction coefficient increases with increasing speed.

The tribological behaviour of water, a lower viscosity Newtonian fluid, was examined and shown in *Figure 4* comparing the MTM and TA systems. The data presented here is different to that of the more viscous vegetable oil, with an extended boundary regime observed for the TA system. The TA system shows boundary and mixed lubrication, whereas the MTM system shows a small amount of boundary, mixed and initial hydrodynamic lubrication behaviour. Again, the systems show a similar trend in friction behaviour where the speeds overlap. The initial increase in friction coefficient below 0.01 mm/s is typical of static friction behaviour due to low sliding speeds (Kieserling et al., 2018).

The correlation coefficient was calculated to show similarities between friction response between comparable sliding speeds (1 mm/s-150 mm/s). When comparing MTM and TA systems, a strong positive correlation coefficient was observed of 0.85 for vegetable oil and 0.96 for water confirming a good agreement with the trend of data for the overlapping speeds for both measurement systems.

3.2. Normal force comparison

Further experiments were performed to examine a range of normal forces (*Figure 5*). Test parameters (speed, SRR, test substrates) were the same as previous experiments but the normal force was changed. Normal forces examined were 0.1 N - 5 N, to explore the range of normal forces reported to be experience in the mouth (Miller and Watkin, 1996). The test lubricant was vegetable oil.

For the MTM, the results at 1 N, 3 N and 5 N normal forces are presented, showing the same lubrication regimes over the speed range tested (*Figure 5a*). The MTM system showed a reduction in friction coefficient with increasing load which can be explained by smoothing of the surfaces due to deformation of the asperities (Prinz et al., 2007). 0.1 N showed high variation due to limitations in normal force control of the equipment so is not presented in this work.

The TA system allowed the measurement of friction at low normal force and speed (*Figure 5b*) as a full Stribeck curve was obtained for the range of normal forces. 0.1 N and 1 N behaved similarly, with a greater friction coefficient at low sliding speeds compared to 3 N and 5 N, which also behaved similarly at these speeds. As with the MTM system, the TA system showed a reduction in friction coefficient with increasing load. A greater reduction in friction coefficient was observed for the MTM system compared to the TA system.

The normal force capability of both instruments was examined further by comparing the average applied normal force to assess accuracy. *Table 2* shows the variation in the control of normal force for both instruments at a range of speeds where they both showed values close to 1 N with overlapping standard deviations.

Table 2 – A comparison of normal force (1 N applied) at different fixed speeds for pure vegetable oil for two different tribological measurement systems (mean ± 1 standard deviation).

Speed (mm/s)	Measured normal force (N)	
	MTM	TA

1	1.03 ± 0.02	1.00 ± 0.04
10	1.03 ± 0.01	0.97 ± 0.04
100	1.01 ± 0.01	1.03 ± 0.06

3.3. Guar gum solutions

The aim of these particular studies were to investigate the friction behaviour of a shear thinning polymer solution. Guar gum solutions of 0.2, 0.4 and 0.6 wt% were tribologically investigated using the MTM and TA systems. There is smooth progression between regimes of all samples tested on the MTM (*Figure 6a*), although only a small section of the hydrodynamic regime was observed for the speed range tested. The friction behaviour transitions from boundary lubrication where the ball and PDMS are in contact, to mixed lubrication as the guar gum solutions begins to be entrained; to the hydrodynamic regime (>100 mm/s) when the guar solutions are fully entrained. Overall for the MTM, there was little difference observed between concentrations of guar gum tested under these conditions and the solutions showed a similar response to water. The TA system showed boundary lubrication and mixed lubrication over at the speed range tested (*Figure 6b*). Below 0.1 mm/s, static friction is observed. The data generally followed the same trend until the speed reached 10 mm/s where definition between the different samples becomes clearer. Above this speed, the mixed regime is entered and guar gum solutions with increasing concentration lubricate more effectively. Below speeds of 0.5 mm/s, greater concentrations of guar gum exhibited the highest friction coefficient. This is likely due to the increased amount of polymer chains of guar gum which have been suggested to block the contact inlet, limiting lubrication of the contacting surfaces (Garrec and Norton, 2012).

For 0.4% guar gum solution, the data from each instrument was compared (*Figure 7*). Above 1 mm/s, friction coefficient decreases as the mixed regime is entered. The MTM and TA data show a similar trend in friction behaviour across the overlapping speed range.

The MTM system shows mixed and hydrodynamic lubrication, but little boundary lubrication. The TA system shows static, boundary and mixed, with little/no hydrodynamic lubrication behaviour at the sliding speed range examined. Both systems observed the main differences between increasing concentrations of guar gum solutions in the mixed regime, as friction coefficient is decreasing with increasing sliding speed. When comparing these results to literature, similar mixed lubrication behaviour has been previously reported by De Vicente, Stokes & Spikes (2004) and Garrec & Norton (2012) who also used an MTM to examine their samples. However, unlike the MTM system, the TA system shows differences between the samples in boundary lubrication where with increasing guar gum concentration, the friction coefficient increases. The MTM does not show the same degree of differentiation in the boundary regime where all samples behave similarly. This could be attributed to only using pure sliding conditions (200% SRR) whereas the studies by De Vicente, Stokes & Spikes (2004) and Garrec & Norton (2012) use a mixture of sliding and rolling conditions; SRR has been shown to affect tribological measurements (Yakubov et al., 2015). It may be of interest to complete further research in order to understand the importance of sliding and rolling conditions to oral processing applications.

3.4. Oil in water emulsions

Oil in water emulsions with 20%, 50% oil as well as pure water (0%) and pure oil (100%) were investigated using the MTM and TA systems. The results for the MTM system do not follow a typical Stribeck curve, there is little distinction between the different samples (*Figure 8a*) with the exception of the 0% oil (pure water) sample discussed previously. The oil is highly lubricating; all oil samples show similar lubrication properties as 100% oil with friction coefficients less than 0.1 across the speeds tested. Results from the TA system for the speed range studied showed with a greater oil content providing greater lubrication (*Figure 8b*). The data observed for 100% oil as previously discussed shows a near perfect Stribeck curve with clear definition of regimes and smooth transition between them. The emulsions demonstrated similar friction response, with boundary lubrication present until around 1 mm/s, where as speed increased mixed lubrication and initial hydrodynamic lubrication were observed.

Whilst the behaviours for both systems are not similar, generally, the MTM showed poor distinction between all samples containing oil whereas the TA system showed distinction between 100% oil and the emulsions. Over the speed range tested, the TA system was successful in showing as much of the Stribeck as possible allowing better comparison of the samples. For the 20% oil emulsion, the data from each instrument was compared (*Figure 9*). Above 10 mm/s, the MTM and TA systems showed similar trends in friction behaviour where the mixed lubrication progresses into hydrodynamic lubrication with increasing speed.

Existing tribological data in literature by Malone et al. (2003) examining emulsions closely resembles the results obtained using the TA system, where boundary and mixed lubrication was observed for oil emulsions and mixed and hydrodynamic lubrication was observed for pure oil. The MTM system demonstrated similar results to Dresselhuis et al. (2007) who reported emulsions exhibiting similar friction coefficient values to pure oil. Friction is determined by oil covering the contact points and/or film formation due to oil release from droplets.

3.5. Soft particulate gels

Agar fluid gel particulate systems of varying concentrations of agar (1, 2, 3 and 4 wt%) were investigated using the MTM and TA systems. The viscosity profiles of agar fluid gels at various agar concentrations were measured (*Figure 10*). All systems showed shear thinning behaviour as expected for interacting particulate systems (Saha and Bhattacharya, 2010). As agar concentration increases, the steady shear viscosity increases across the shear rates examined.

The friction measurements for the MTM system showed some mixed and hydrodynamic lubrication (*Figure 11a*). As speed was increased to 100 mm/s, friction coefficient decreases for all samples. As speed increased above 100 mm/s, friction coefficient gradually increases. Above 100 mm/s, the agar fluid gels show with greater increase in concentration of agar the poorer the lubrication. Increasing concentration of agar is said to increase particle rigidity (Gabriele, 2011). For the less rigid fluid gel systems with lower concentrations of agar, it is likely particles are able to be entrained by squeezing into the gap. For the more rigid particles at higher concentration, where the friction coefficient changes very little over the speed range tested, it could be possible only few particles are able enter the gap so the remainder are building up around the contact area thus increasing friction. For the speed range studied, the TA system exhibited static, boundary and mixed lubrication with increasing speed (*Figure 11b*). Above 0.05 mm/s, clear distinction between agar concentrations becomes apparent; where with a greater concentration of agar, there was a lower friction coefficient.

For 4% agar fluid gel, the data from each instrument were compared (*Figure 12*). A difference in friction behaviour can be seen between the systems, where the TA systems shows an unusual increase in friction coefficeint around 10 mm/s. This can be described as a micro-EHL regime, also observed by A Gabriele, Spyropoulos, & Norton (2010). This regime describes how at low sliding speeds only the fluid medium can access the gap between the ball and the disk, and as speed increases particle entrainment begins which results in an increase in the values of the friction coefficient as gap size is similar to particle size. As speed increases further, more particles are entrained and this decreases the friction coefficient. This is not present with the MTM; possibly due to the limited amount of mixed lubrication observed in the speed range tested. If lower speeds could be achieved, it may be possible this behaviour is present under these conditions. The differences in friction coefficient between the two systems with the agar fluid gel may be due to differences in contact area and pressures. The smaller contact area and greater contact pressure may act to limit the amount of particles in the contact, increasing friction coefficient for the TA system compared to the MTM system. Futher research is required to understand how contact area and pressures affect entrainment of particulate systems like agar fluid gels.

Measurements performed using the TA system was able to demonstrate similarities in friction response to the established MTM system for some model food-based formulations. These results indicate that friction measurements of simple systems depend less on the specific geometry compared to more complex systems. The TA and MTM systems showed agreement and similar trends in the Newtonian fluids, guar gum and oil in water emulsions when the speeds overlapped. Differences were observed between the TA and MTM systems for soft gel particles; although, it has been previously reported particulate systems are difficult to measure tribologically (Yakubov et al., 2015). Both systems were comparable to similar studies in literature. The TA system afforded boundary lubrication features of the Stribeck curve due to achieving lower speeds compared to the MTM. This finding is useful for researchers interested in boundary lubrication where surfaces are in contact. However, at very low speeds there is a larger associated error between measurements; likely due to stick-slip behaviour between the contacting surfaces (Goh et al., 2010; Zhang and Meng, 2015). The Discovery HR-2 three-ball-on-plate tribology geometry is flexible but the contact area is small, meaning for a given normal force a high pressure is applied when compared to the MTM system. This may be good for some applications where high pressures are representative of a process, like mimicking joints. However, it is also possible to examine samples at low contact pressures, as normal forces lower than 1 N can be used successfully with soft surfaces unlike the MTM, which may be relevant to some biological, soft tribology applications.

4. Conclusions and future work

The friction properties of a range of model food like systems were measured using a three-ball-on-plate rheometer attachment and compared to measurements obtained from an MTM. Testing using a soft surface showed similarities between the two different testing equipment for simple systems, showing the friction results depend less on the specific geometry compared to complex systems. The data yielded was also comparable to existing studies in literature. The TA system allowed the boundary lubrication regime to be examined for all samples due to achieving lower speeds compared to the MTM; speeds as low as 0.02 mm/s are able to be tested using the Discovery HR-2 rheometer. The rheometer however, is limited to sliding friction only. For the guar gum solutions and oil in water emulsions, the three-ball-on plate friction data showed similar trends when compared to MTM data, with relative distinctions between the different samples. However, for the soft particulate system, discrepancies were observed likely as a result of particle entrainment being affected by difference in contact area. As there are many parameters that can affect tribological measurements, including the testing equipment, it is clear more work needs to be done to determine ideal testing conditions to be able to successfully analyse food products, which are often particulate in nature. Ideally, a standard protocol for measurements using a rheometer with tribology attachment should be determined and adopted. It is recommended further studies are completed to compare friction data obtained using a rheometer to sensory data with the intent of finding relationships between quantitative measurements and texture perception.

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6. References

Anvari, M., Joyner (Melito), H.S., 2017. Effect of formulation on structure-function relationships of concentrated emulsions: Rheological, tribological, and microstructural characterization. Food Hydrocoll. 72, 11–26. https://doi.org/10.1016/j.foodhyd.2017.04.034

Bongaerts, J.H.H., Fourtouni, K., Stokes, J.R., 2007. Soft-tribology: Lubrication in a compliant PDMS-PDMS contact. Tribol. Int. 40, 1531–1542. https://doi.org/10.1016/j.triboint.2007.01.007

Chen, J., Stokes, J.R., 2012. Rheology and tribology: Two distinctive regimes of food texture sensation. Trends Food Sci. Technol. 25, 4–12. https://doi.org/10.1016/j.tifs.2011.11.006

Chojnicka-Paszun, A., De Jongh, H.H.J., De Kruif, C.G., 2012. Sensory perception and lubrication properties of milk: Influence of fat content. Int. Dairy J. 26, 15–22. https://doi.org/10.1016/j.idairyj.2012.04.003

Chojnicka, A., De Jong, S., De Kruif, C.G., Visschers, R.W., 2008. Lubrication properties of protein aggregate dispersions in a soft contact. J. Agric. Food Chem. https://doi.org/10.1021/jf0720988

De Vicente, J., Stokes, J.R., Spikes, H.A., 2004. Lubrication properties of non-adsorbing polymer solutions in soft elastohydrodynamic (EHD) contacts. Tribol. Int. 38, 512–526. https://doi.org/10.1016/j.triboint.2004.11.001

de Wijk, R.A., Prinz, J.F., 2004. The role of friction in perceived oral texture. Food Qual. Prefer. 16, 121–129. https://doi.org/10.1016/j.foodqual.2004.03.002

Dickinson, E., 2003. Hydrocolloids at interfaces and the influence on the properties of dispersed systems. Food Hydrocoll. 17, 25–39. https://doi.org/10.1016/S0268-005X(01)00120-5

Douaire, M., Stephenson, T., Norton, I.T., 2014. Soft tribology of oil-continuous emulsions. J. Food Eng. 139, 24–30. https://doi.org/10.1016/j.jfoodeng.2014.04.007

Dresselhuis, D.M., de Hoog, E.H.A., Cohen Stuart, M.A., van Aken, G.A., 2008. Application of oral tissue in tribological measurements in an emulsion perception context. Food Hydrocoll. 22, 323–335. https://doi.org/10.1016/j.foodhyd.2006.12.008

Dresselhuis, D.M., Jan Klok, H., Cohen Stuart, M.A., de Vries, R.J., van Aken, G.A., A de Hoog, E.H., 2007. Tribology of o/w Emulsions Under Mouth-like Conditions: Determinants of Friction. https://doi.org/10.1007/s11483-007-9040-9

Ellis, A.L., Norton, A.B., Mills, T.B., Norton, I.T., 2017. Stabilisation of foams by agar gel particles. Food Hydrocoll. 73, 222–228. https://doi.org/10.1016/J.FOODHYD.2017.06.038

Fernández Farrés, I., Norton, I.T., 2015. The influence of co-solutes on tribology of agar fluid gels. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2014.11.014

Gabriele, A., 2011. Fluid gels: Formation, production and lubrication.

Gabriele, A., Spyropoulos, F., Norton, I.T., 2010. A conceptual model for fluid gel lubrication. Soft Matter 6, 4205–4213. https://doi.org/10.1039/c001907k

Garrec, D.A., Norton, I.T., 2012. The influence of hydrocolloid hydrodynamics on lubrication. Food Hydrocoll. 26, 389–397. https://doi.org/10.1016/j.foodhyd.2011.02.017

Goh, S.M., Versluis, P., Appelqvist, I.A.M., Bialek, L., 2010. Tribological measurements of foods using a rheometer. Food Res. Int. 43, 183–186. https://doi.org/10.1016/j.foodres.2009.09.024

Hailing, J., 1991. Encyclopedia of tribology, Wear. https://doi.org/10.1016/0043-1648(91)90333-P

Joyner, H.S., Pernell, C.W., Daubert, C.R., 2014. Impact of formulation and saliva on acid milk gel friction behavior. J. Food Sci. 79. https://doi.org/10.1111/1750-3841.12439

Joyner (Melito), H.S., Pernell, C.W., Daubert, C.R., 2014. Beyond surface selection: The impact of different methodologies on tribological measurements. J. Food Eng. 134, 45–58. https://doi.org/10.1016/j.jfoodeng.2014.03.003

Kieserling, K., Schalow, S., Drusch, S., 2018. Method Development and Validation of Tribological Measurements for Differentiation of Food in a Rheometer. Biotribology 16, 25–34. https://doi.org/10.1016/J.BIOTRI.2018.09.002

Krzeminski, A., Wohlhüter, S., Heyer, P., Utz, J., Hinrichs, J., 2012. Measurement of lubricating properties in a tribosystem with different surface roughness. Int. Dairy J. https://doi.org/10.1016/j.idairyj.2012.02.005

Malone, M.E., Appelqvist, I.A.M., Norton, I.T., 2003. Oral behaviour of food hydrocolloids and emulsions. Part 1. Lubrication and deposition considerations. Food Hydrocoll. 17, 763–773. https://doi.org/10.1016/S0268-005X(03)00097-3

Miller, J.L., Watkin, K.L., 1996. The influence of bolus volume and viscosity on anterior lingual force during the oral stage of swallowing. Dysphagia 11, 117–124. https://doi.org/10.1007/BF00417901

Myant, C., Spikes, H.A., Stokes, J.R., 2010. Influence of load and elastic properties on the rolling and sliding friction of lubricated compliant contacts. Tribol. Int. 43, 55–63. https://doi.org/10.1016/j.triboint.2009.04.034

Pradal, C., Stokes, J.R., 2016. Oral tribology: Bridging the gap between physical measurements and sensory experience. Curr. Opin. Food Sci. 9, 34–41. https://doi.org/10.1016/j.cofs.2016.04.008

Prinz, J.F., de Wijk, R.A., Huntjens, L., 2007. Load dependency of the coefficient of friction of oral mucosa. Food Hydrocoll. 21, 402–408. https://doi.org/10.1016/j.foodhyd.2006.05.005

Rodrigues, S.A., Selway, N., Morgenstern, M.P., Motoi, L., Stokes, J.R., James, B.J., 2017. Lubrication of chocolate during oral processing 8. https://doi.org/10.1039/c6fo00950f

Saha, D., Bhattacharya, S., 2010. Hydrocolloids as thickening and gelling agents in food: a critical review. J. Food Sci. Technol. 47, 587–597. https://doi.org/10.1007/s13197-010-0162-6

Sarkar, A., Andablo-Reyes, E., Bryant, M., Dowson, D., Neville, A., 2019. Lubrication of soft oral surfaces. Curr. Opin. Colloid Interface Sci. 39, 61–75. https://doi.org/10.1016/J.COCIS.2019.01.008

Yakubov, G.E., Branfield, T.E., Bongaerts, J.H.H., Stokes, J.R., 2015. Tribology of particle suspensions in rolling-sliding soft contacts. Biotribology 3, 1–10. https://doi.org/10.1016/j.biotri.2015.09.003

Zhang, J., Meng, Y., 2015. Boundary lubrication by adsorption film. Friction 3, 115–147. https://doi.org/10.1007/s40544-015-0084-4

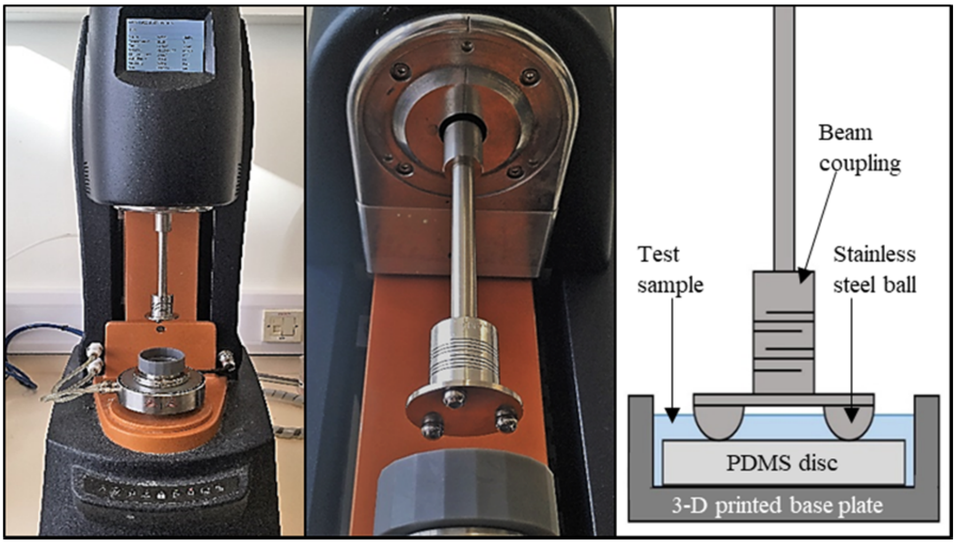

Figure 1 – Three-ball-on-plate tribology attachment for the Discovery HR-2 rheometer by TA Instruments.

Figure 2 – Photographs of 3-D printed base plate (tribometer cell) for holding the PDMS disc.

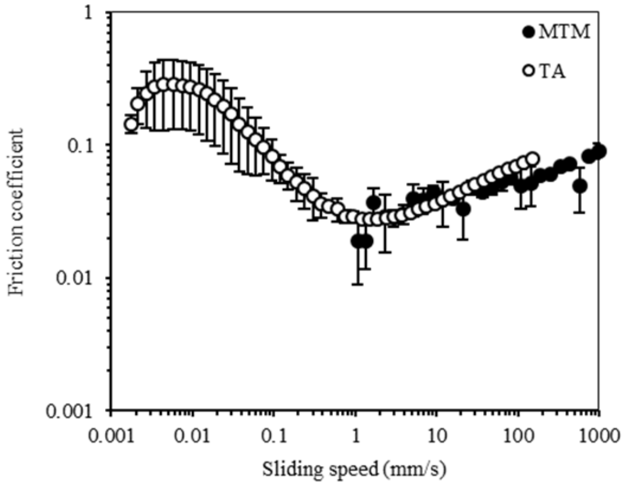

Figure 3 – Friction coefficient vs sliding speed of vegetable oil with the two different tribological measurement systems at normal force 1 N.

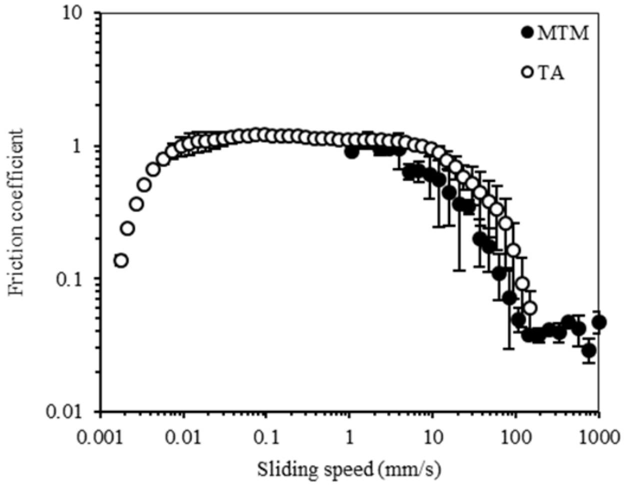

Figure 4 – Friction coefficient vs sliding speed of water with the two different tribological measurement systems at normal force 1 N.

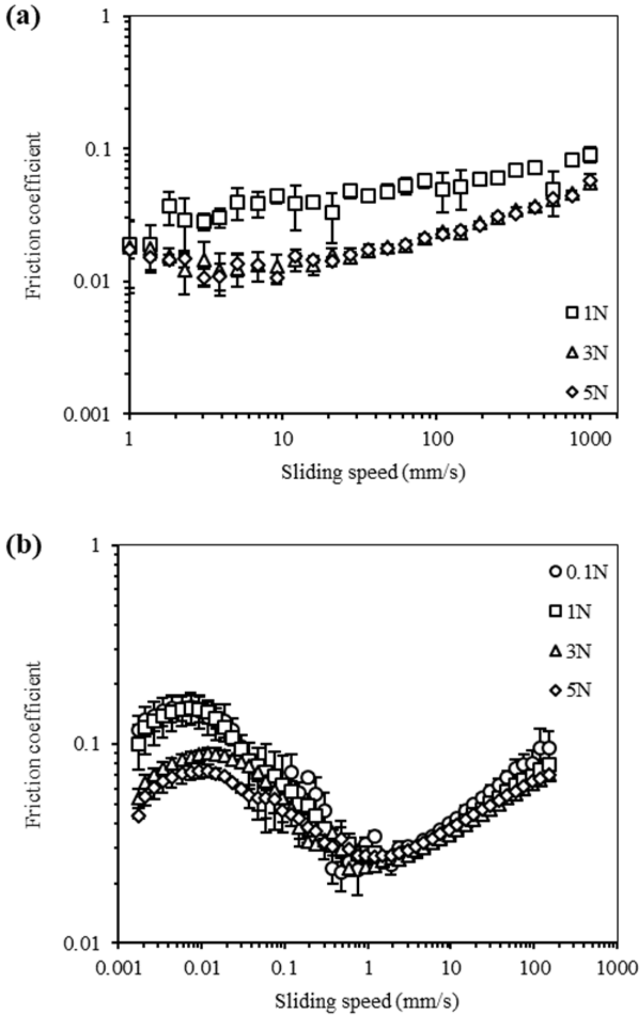

Figure 5 - A comparison of normal force for pure vegetable oil performed by (a) MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate tribology attachment.

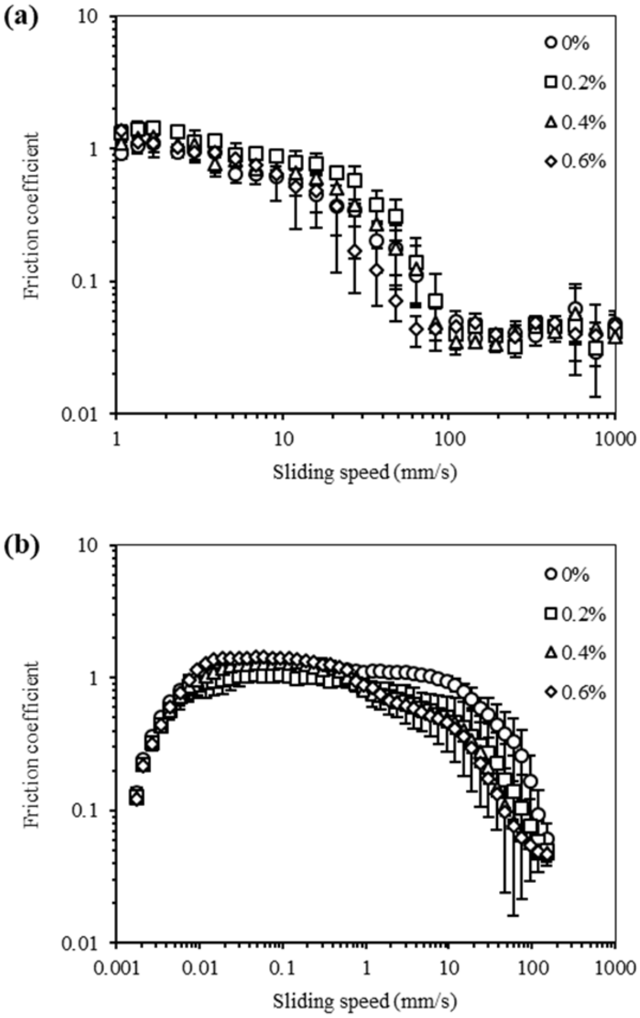

Figure 6 – Friction coefficient vs sliding speed of guar gum solutions of varying concentration measured using (a) MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate tribology attachment at normal force 1 N.

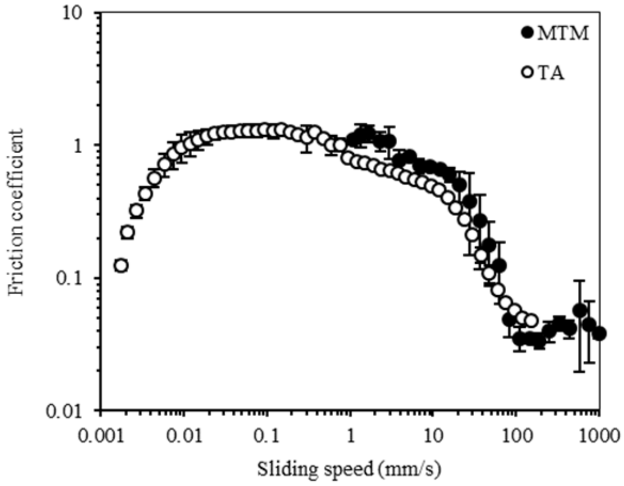

Figure 7 - Friction coefficient vs sliding speed of 0.4% guar gum solution with the two different tribological measurement systems at normal force 1 N.

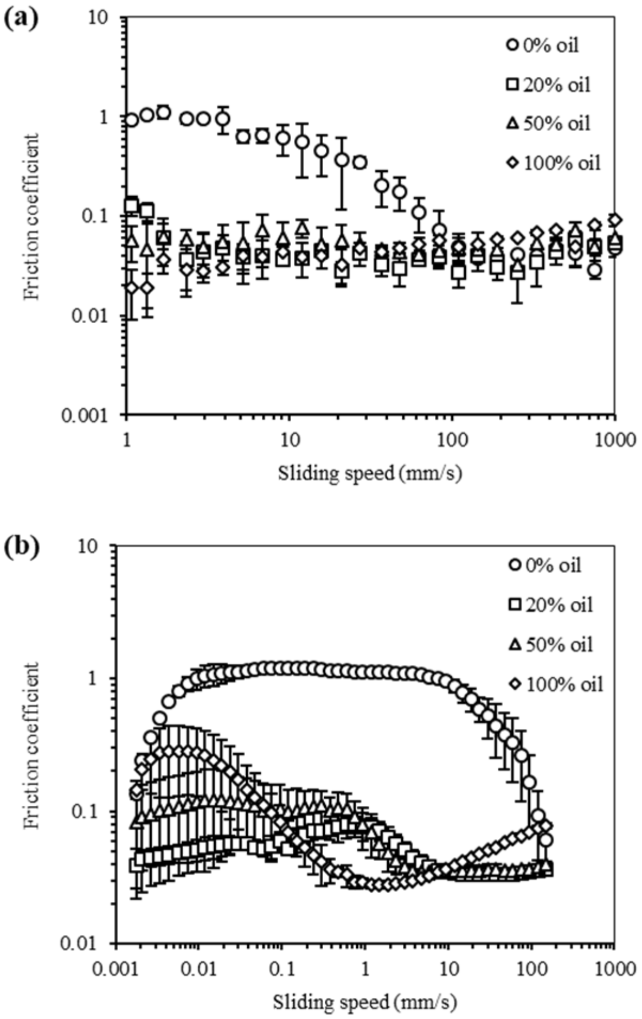

Figure 8 - Friction coefficient vs sliding speed of oil in water emulsions of varying oil concentration measured using (a) MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate tribology attachment at normal force 1 N.

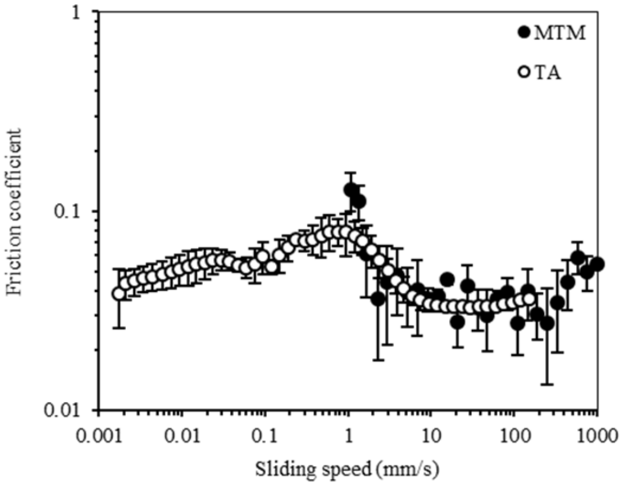

Figure 9 - Friction coefficient vs sliding speed of 20% oil emulsion with the two different tribological measurement systems at normal force 1 N.

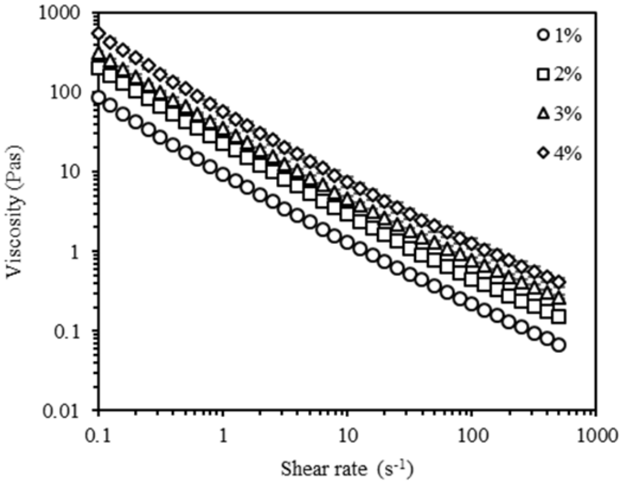

Figure 10 – The shear rheology for agar fluid gels of varying concentrations.

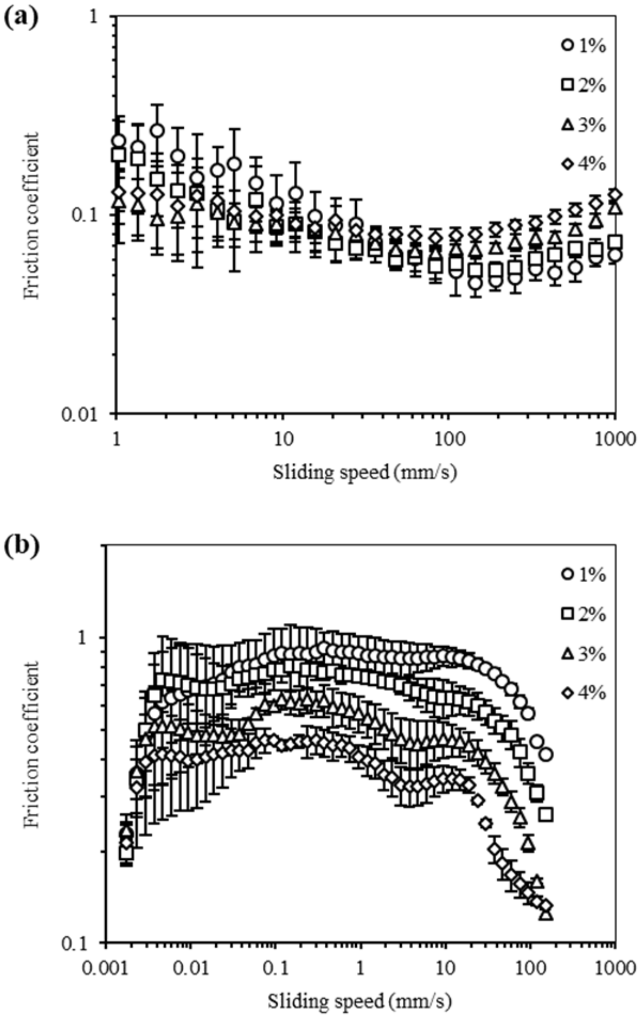

Figure 11 - Friction coefficient vs sliding speed of agar fluid gels of varying concentration measured using (a) MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate tribology attachment at normal force 1 N.

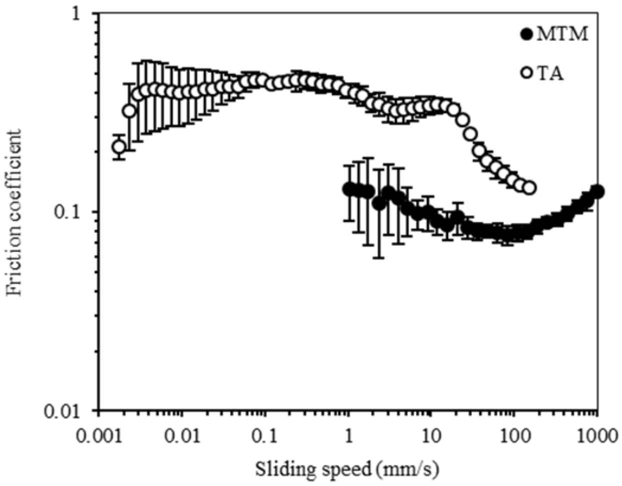

Figure 12 - Friction coefficient vs sliding speed of 4% agar fluid gel with the two different tribological measurement systems at normal force 1 N.