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

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

5 Abstract

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

19 1. Introduction

20 Traditionally tribology, the study of friction, lubrication and wear, has been used to determine the
21 properties of systems concerning contacting surfaces like machine components and bearings (Hailing,
22 1991). More recently, tribology has been used with focus on oral processing to study the frictional
23 properties of food systems, for example oil-in-water emulsions (Chojnicka et al., 2008; Dresselhuis et
24 al., 2007), dairy products (Chojnicka-Paszun et al., 2012; Joyner et al., 2014) and chocolate
25 (Rodrigues et al., 2017). Tribological measurements of foods are generally performed on soft
26 surfaces, such as rubbers, silicones and biological tissues as these more closely resemble oral surfaces
27 than typical steel-steel contacts (Bongaerts et al., 2007; Chen and Stokes, 2012; Dresselhuis et al.,
28 2008; Sarkar et al., 2019). Tribometers, like the Mini-Traction Machine (MTM) by PCS Instruments
29 (Garrec and Norton, 2012; Myant et al., 2010), custom-made laboratory apparatus (de Wijk & Prinz,
30 2004; Dresselhuis et al., 2008) or rheometers with tribological attachments (Kieserling et al., 2018;
31 Krzeminski et al., 2012) have all been used to understand the tribological properties of foods. Many
32 rheometer manufacturers now offer tribology attachments for their instruments. These systems vary
33 between instrument manufacturers but generally consist of a rotating aspect and a stationary aspect.
34 The contacts can be plates, balls, discs or rings and can consist of two or more contacting surfaces.
35 For example Joyner (Melito) et al. (2014) investigates two tribological apparatus: ball-on-three-plate
36 and double-ball-on-plate. The authors found the tribological measurement system did not affect
37 friction regimes observed for each material, but did affect the magnitude of friction coefficient. The
38 difference in these results were attributed to the set-up of the contacting surfaces as the double-ball
39 system had a horizontal plate; whereas the ball-on-three-plate system had angled plates meaning
40 lubricant flowed off them and measurements were not accurate.

41 Using a rheometer for tribological applications is advantageous as a range of normal forces, speeds
42 and testing surfaces can be examined with ease suggesting this method can provide similar
43 information to other commercially available tribometers. The advantage of using the rheometer
44 attachment for tribology measurements would be reduced cost and advanced measurement techniques
45 for institutions that own or have use of a rheometer, but cannot warrant the purchase of a specialist

46 piece of equipment for tribology. Rheometer based tribological measurements are relevant for food
47 applications as many food scientists already own a rheometer. In this study, a three-ball-on-plate
48 rheometer attachment is compared to a Mini Traction Machine (MTM), which is well established for
49 use in soft surface tribology. The MTM consists of a disc mounted in a sample pot onto which a ball
50 on a shaft is lowered to be in contact with at a 45° angle. Entrainment occurs between these surfaces
51 as they rotate. Entrainment for the rheometer relies on the mounting plate repelling from the rotating
52 geometry; separating to allow lubricant in between. The plate/disc surface in the rheometer is
53 stationary giving only pure sliding friction measurements, whereas for the MTM a mixture of sliding
54 and rolling friction can be used as both surfaces are able to rotate independently. During oral
55 processing, the tongue moves up and down, pressing the food against the palate in order to process it.
56 Since the palate does not move, it can be assumed that sliding motions likely dominate in the mouth.
57 However, in practice this process is more complex as mastication, saliva incorporation and tongue
58 motion mean food experiences both sliding and rolling motions (Chojnicka et al., 2008).

59 This study aims to use a range of previously tribologically examined model food systems. These
60 include Newtonian fluids, a shear-thinning hydrocolloid solution, a simple emulsion and a soft
61 particulate system. Hydrocolloids cover a wide range of materials, including a variety of
62 polysaccharides and gums. These are widely used in food formulations as thickeners, rheology
63 modifiers and gelling agents which give structure and specific textural properties to the product
64 (Dickinson, 2003). Guar gum is frequently reported in literature due to its extensive use in foods and
65 Non-Newtonian shear thinning behaviour. Malone previously studied guar gum tribologically finding
66 correlation between concentration and oral perceived slipperiness (Malone et al., 2003). The use of
67 emulsions in food is commonplace; both in manufactured and processed foods, and natural products
68 like milk. Emulsions give textural (for example creaminess, oiliness) and taste to a product. The basic
69 structure of an emulsion consists of two immiscible liquids, typically an oil phase and an aqueous
70 phase. One is dispersed in the form of droplets within the other. Food based emulsions have been well
71 examined tribologically (Anvari and Joyner (Melito), 2017; Douaire et al., 2014; Dresselhuis et al.,
72 2007; Malone et al., 2003). A range of gels are used in food applications where the gelation process

73 leads to a quiescent gel. The gelation process can be modified by applying shear during the cooling
74 process, allowing discrete gel particles to form in suspensions. The resultant material, a fluid gel, is
75 both solid-like and liquid-like. These gels are increasingly being used as fat replacement, due to being
76 able to impart structural properties whilst comprising of mostly water. These show non-typical
77 Stribeck behaviour so will be of interest to compare in this work (Fernández Farrés and Norton, 2015;
78 Gabriele et al., 2010).

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

88 2. Materials and methods

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

93 2.1. Disc preparation

94 Discs were fabricated using a two-part kit (Sylgard 184) consisting of silicone elastomer and curing
95 agent which were mixed in the manufacturers recommended 10:1 ratio. The binary mixture was
96 poured into a sheet of 4 mm thickness, degassed and placed in an oven at 70 °C for 2 hours. The sheet
97 was left to cool for at least 24 hours and discs were cut out for use in the tribometer using a 46 mm
98 diameter disc cutter. Before all tests, PDMS discs and steel balls were sonically cleaned in

99 isopropanol followed by distilled water for 6 minutes each. They were dried in air and fitted into the
100 tribometer cell. Each disc was used for one experiment and then discarded.

101 2.2. Guar gum solutions

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

106 2.3. Oil in water emulsions

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

113 2.4. Soft particulate gels

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

124 2.5. Shear rheology

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

130 2.6. Tribology

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

137 2.6.1. Mini-traction machine

138 A mini traction machine (MTM) manufactured by PCS Instruments, UK was used to perform
139 tribological measurements to compare data obtained from the rheometers. The MTM consists of a ball
140 loaded onto a disc producing a small point of contact where material can be assessed. The ball and
141 disc are independently driven which gives precise control over speeds and direction of rotation of the
142 contacting surfaces as well as ratio of speeds of the contacts. The MTM also allows for control over
143 applied normal force. As the rheometer only has sliding functionality, pure sliding conditions of 200%
144 slide-roll-ratio (SRR) was used. Three tests of ascending sliding speed 1 to 1000 mm/s were
145 completed and the average reported. A volume reducing insert was used allowing for a sample size of
146 15 mL. Experiments were performed at room temperature (25°C). A normal force of 1 N was used
147 (unless stated otherwise) as in mouth friction was reported to be between 0.1 N and 10 N (Miller and
148 Watkin, 1996). 1 N would allow low contact pressure, which is of relevance in oral processing
149 applications.

150 2.6.2. Tribology attachment for rheometer

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

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

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

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

158 Flow sweeps were performed measuring torque through a range of applied velocities at equilibrium
159 (0.0001 to 10 radians/s where the linear speed equates to ~ 0.002 to 150 mm/s sliding speed) with ten
160 measurements per decade (50 measurements total) at room temperature (25 °C) and normal force of 1
161 N, unless stated otherwise. During testing, the PDMS disc was secured using a custom 3-D printed
162 base plate seen in *Figure 2* and visible in *Figure 1*. A sample volume of 15 mL was used. Each
163 sample was tested three times and an average obtained.

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

168 *Table 1 – The ball diameter, contact area and average contact pressure at 1 N for the stainless steel ball and*
169 *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 x 10 ⁻⁶	185

TA	¼ inch (0.003175)	3.7×10^{-6}	270
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170

171 3. Results and discussion

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

179 3.1. Newtonian fluids

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

186 The tribological behaviour of water, a lower viscosity Newtonian fluid, was examined and shown in
 187 *Figure 4* comparing the MTM and TA systems. The data presented here is different to that of the
 188 more viscous vegetable oil, with an extended boundary regime observed for the TA system. The TA
 189 system shows boundary and mixed lubrication, whereas the MTM system shows a small amount of
 190 boundary, mixed and initial hydrodynamic lubrication behaviour. Again, the systems show a similar
 191 trend in friction behaviour where the speeds overlap. The initial increase in friction coefficient below
 192 0.01 mm/s is typical of static friction behaviour due to low sliding speeds (Kieserling et al., 2018).

193 The correlation coefficient was calculated to show similarities between friction response between
 194 comparable sliding speeds (1 mm/s-150 mm/s). When comparing MTM and TA systems, a strong

195 positive correlation coefficient was observed of 0.85 for vegetable oil and 0.96 for water confirming a
196 good agreement with the trend of data for the overlapping speeds for both measurement systems.

197 3.2. Normal force comparison

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

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

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

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

217 *Table 2 – A comparison of normal force (1 N applied) at different fixed speeds for pure vegetable oil for two*
218 *different tribological measurement systems (mean \pm 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

219

220 3.3. Guar gum solutions

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

237

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

241 The MTM system shows mixed and hydrodynamic lubrication, but little boundary lubrication. The
 242 TA system shows static, boundary and mixed, with little/no hydrodynamic lubrication behaviour at
 243 the sliding speed range examined. Both systems observed the main differences between increasing
 244 concentrations of guar gum solutions in the mixed regime, as friction coefficient is decreasing with

245 increasing sliding speed. When comparing these results to literature, similar mixed lubrication
246 behaviour has been previously reported by De Vicente, Stokes & Spikes (2004) and Garrec & Norton
247 (2012) who also used an MTM to examine their samples. However, unlike the MTM system, the TA
248 system shows differences between the samples in boundary lubrication where with increasing guar
249 gum concentration, the friction coefficient increases. The MTM does not show the same degree of
250 differentiation in the boundary regime where all samples behave similarly. This could be attributed to
251 only using pure sliding conditions (200% SRR) whereas the studies by De Vicente, Stokes & Spikes
252 (2004) and Garrec & Norton (2012) use a mixture of sliding and rolling conditions; SRR has been
253 shown to affect tribological measurements (Yakubov et al., 2015). It may be of interest to complete
254 further research in order to understand the importance of sliding and rolling conditions to oral
255 processing applications.

256 3.4. Oil in water emulsions

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

268 Whilst the behaviours for both systems are not similar, generally, the MTM showed poor distinction
269 between all samples containing oil whereas the TA system showed distinction between 100% oil and
270 the emulsions. Over the speed range tested, the TA system was successful in showing as much of the
271 Stribeck as possible allowing better comparison of the samples. For the 20% oil emulsion, the data

272 from each instrument was compared (*Figure 9*). Above 10 mm/s, the MTM and TA systems showed
273 similar trends in friction behaviour where the mixed lubrication progresses into hydrodynamic
274 lubrication with increasing speed.

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

281 3.5. Soft particulate gels

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

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

297 speed (*Figure 11b*). Above 0.05 mm/s, clear distinction between agar concentrations becomes
298 apparent; where with a greater concentration of agar, there was a lower friction coefficient.

299

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

315 Measurements performed using the TA system was able to demonstrate similarities in friction
316 response to the established MTM system for some model food-based formulations. These results
317 indicate that friction measurements of simple systems depend less on the specific geometry compared
318 to more complex systems. The TA and MTM systems showed agreement and similar trends in the
319 Newtonian fluids, guar gum and oil in water emulsions when the speeds overlapped. Differences were
320 observed between the TA and MTM systems for soft gel particles; although, it has been previously
321 reported particulate systems are difficult to measure tribologically (Yakubov et al., 2015). Both
322 systems were comparable to similar studies in literature. The TA system afforded boundary
323 lubrication features of the Stribeck curve due to achieving lower speeds compared to the MTM. This

324 finding is useful for researchers interested in boundary lubrication where surfaces are in contact.
325 However, at very low speeds there is a larger associated error between measurements; likely due to
326 stick-slip behaviour between the contacting surfaces (Goh et al., 2010; Zhang and Meng, 2015). The
327 Discovery HR-2 three-ball-on-plate tribology geometry is flexible but the contact area is small,
328 meaning for a given normal force a high pressure is applied when compared to the MTM system. This
329 may be good for some applications where high pressures are representative of a process, like
330 mimicking joints. However, it is also possible to examine samples at low contact pressures, as normal
331 forces lower than 1 N can be used successfully with soft surfaces unlike the MTM, which may be
332 relevant to some biological, soft tribology applications.

333 4. Conclusions and future work

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

350 rheometer to sensory data with the intent of finding relationships between quantitative measurements
351 and texture perception.

352 5. Acknowledgements

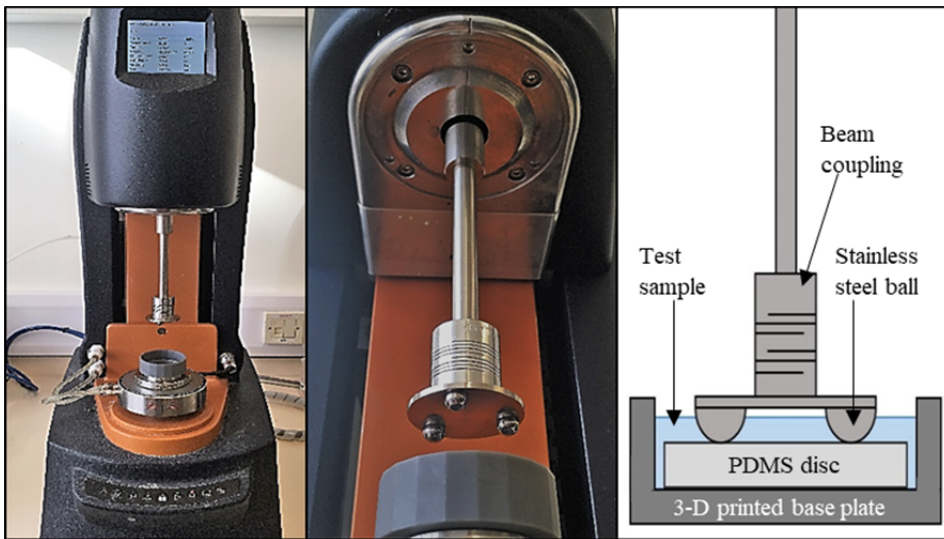
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354 the tribology attachment measurements.

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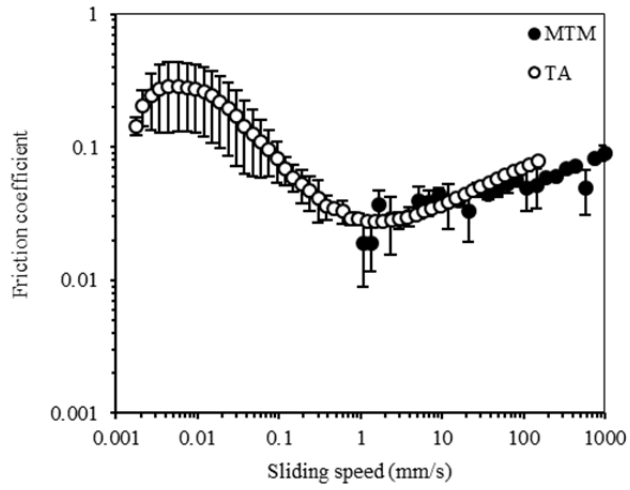
433 *Figure 1 – Three-ball-on-plate tribology attachment for the Discovery HR-2 rheometer by TA Instruments.*



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

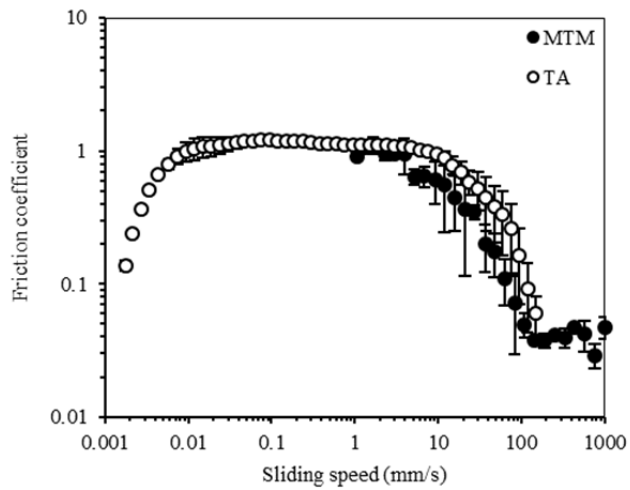
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438 *Figure 3 – Friction coefficient vs sliding speed of vegetable oil with the two different tribological measurement*

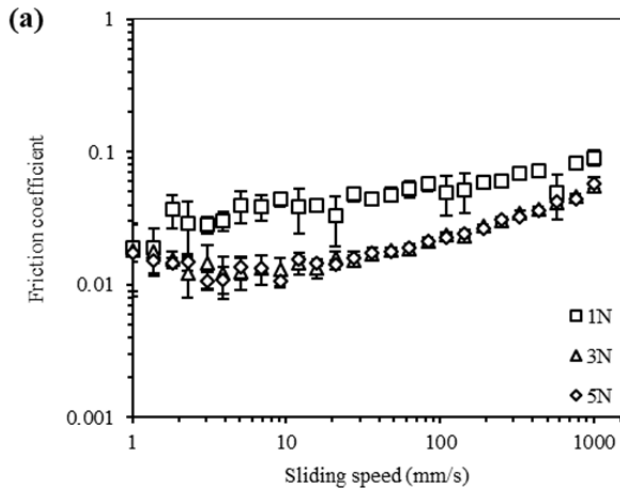
439 *systems at normal force 1 N.*



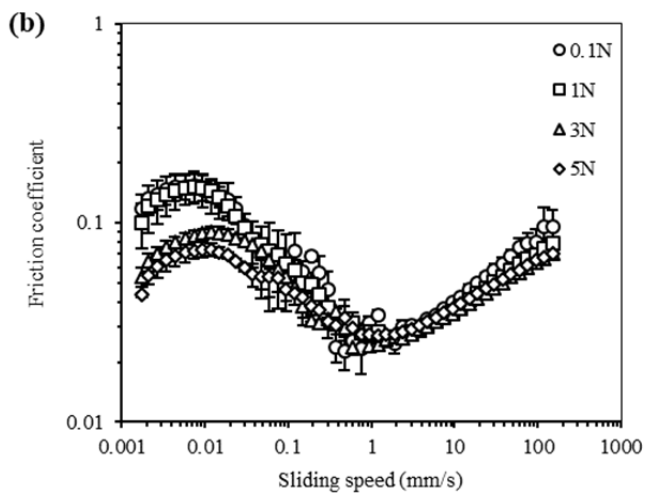
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441 *Figure 4 – Friction coefficient vs sliding speed of water with the two different tribological measurement systems*

442 *at normal force 1 N.*



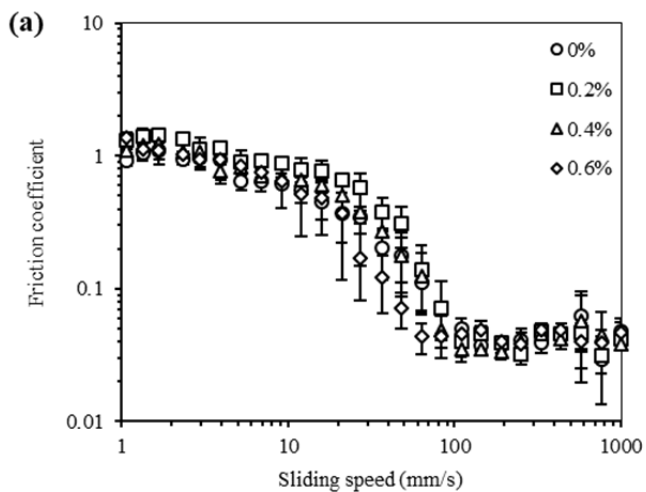
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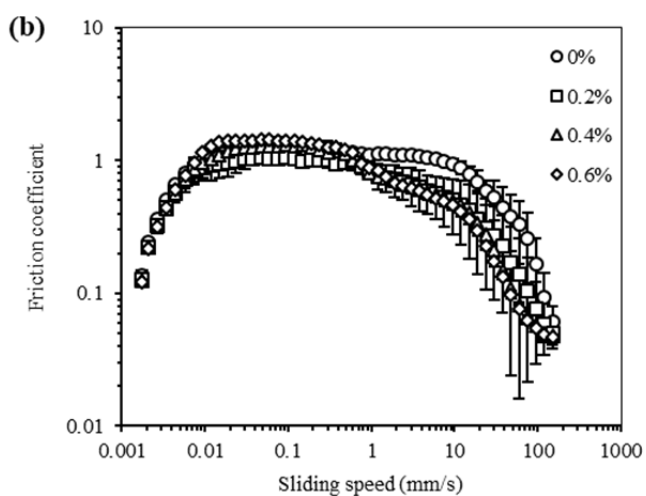
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445 *Figure 5 - A comparison of normal force for pure vegetable oil performed by (a) MTM by PCS Instruments and*
 446 *(b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate tribology attachment.*

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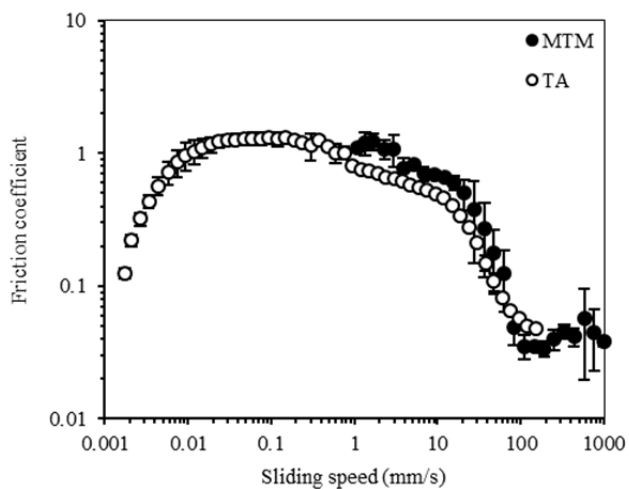


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449

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

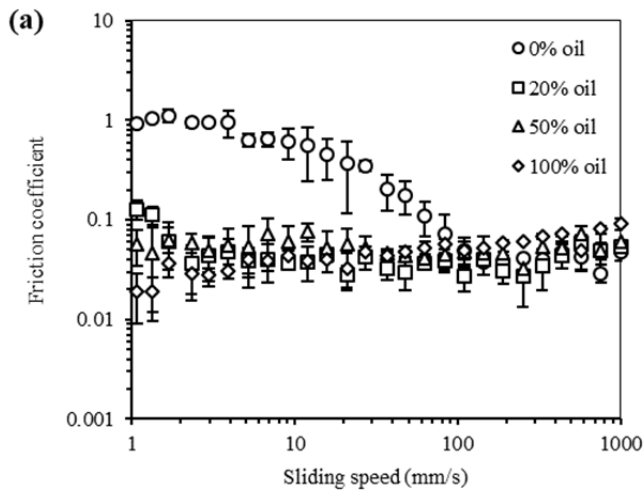


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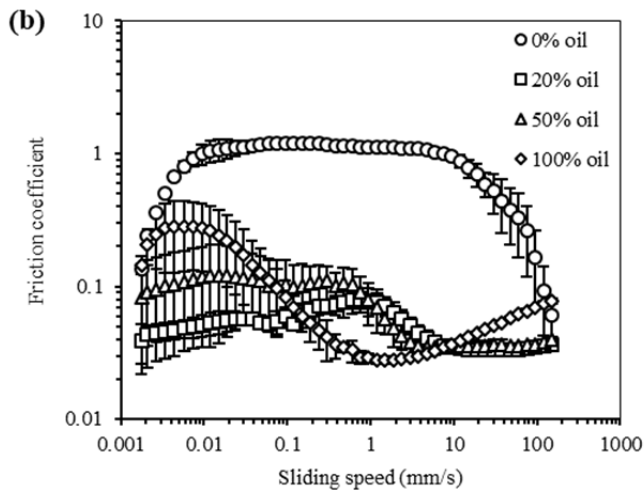
454 *Figure 7 - Friction coefficient vs sliding speed of 0.4% guar gum solution with the two different tribological*
455 *measurement systems at normal force 1 N.*

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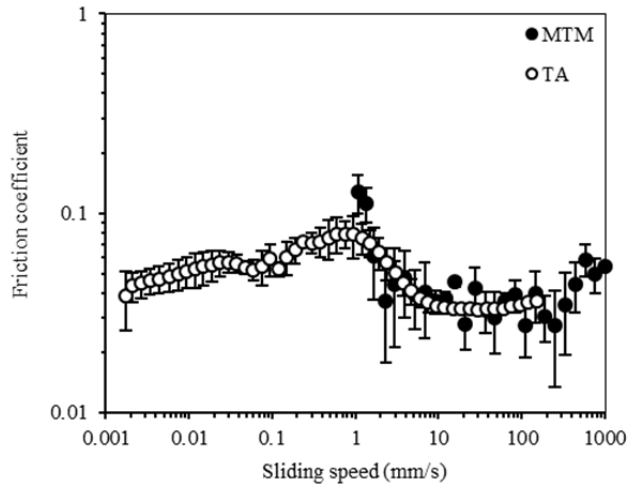


459

460 *Figure 8 - Friction coefficient vs sliding speed of oil in water emulsions of varying oil concentration measured*

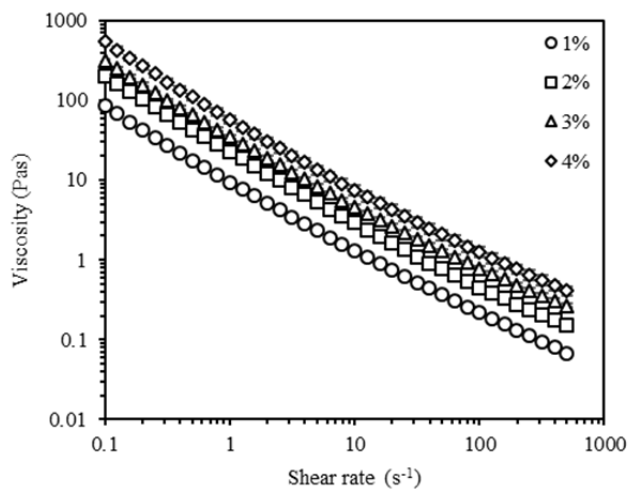
461 *using (a) MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-*

462 *plate tribology attachment at normal force 1 N.*



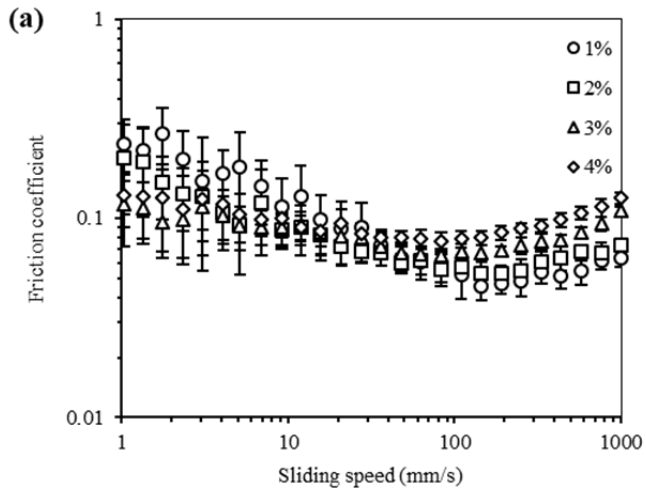
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464 *Figure 9 - Friction coefficient vs sliding speed of 20% oil emulsion with the two different tribological*
 465 *measurement systems at normal force 1 N.*

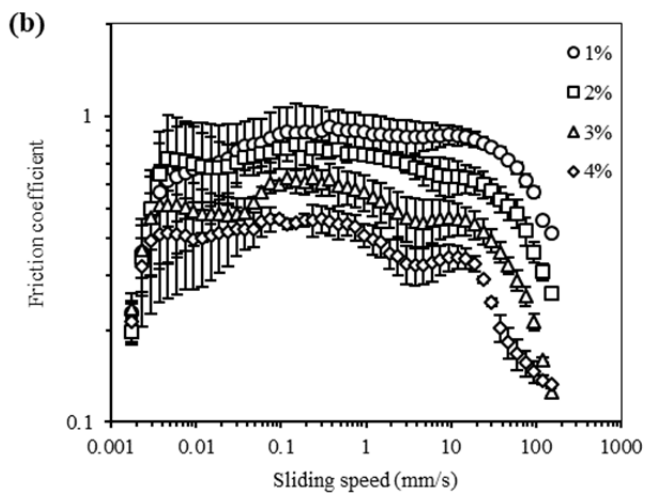


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467 *Figure 10 – The shear rheology for agar fluid gels of varying concentrations.*



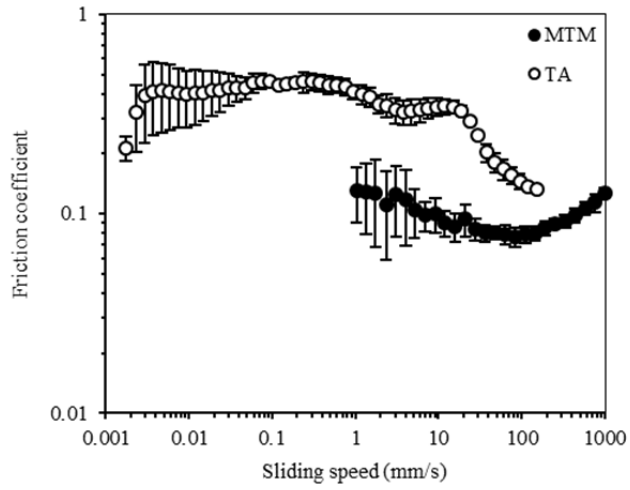
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470 *Figure 11 - Friction coefficient vs sliding speed of agar fluid gels of varying concentration measured using (a)*
 471 *MTM by PCS Instruments and (b) Discovery HR-2 rheometer by TA Instruments with three-ball-on-plate*
 472 *tribology attachment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

473



474

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

477