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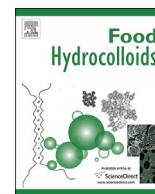
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Stabilisation of foams by agar gel particles



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ABSTRACT

The increasing consumer demand for low fat foods has resulted in a need to replace fat in whipped products with natural, readily available food ingredients. Agar fluid gels with the ability to stabilise foams are therefore presented. Gelled particles can be used to mimic fat droplets and also stabilise foams through localised jamming of the interstitial fluid in foam channels, which considerably slows drainage. Innovative processing has developed fluid gels for the functionality of aeration that has built upon this understanding. Novel particle shapes were manufactured, which enhanced particle interaction and ultimately improved their functionality when aerated. The properties of agar gelled particles were controlled by altering agar concentration. Foam stability at each concentration was assessed in terms of half-life measurements. While most exhibited a half-life of around 24 h, there was a dramatic increase at 3 wt% agar, which displayed a half-life of six days. A critical yield stress of the suspending fluid at 3 wt% had therefore been reached, which resulted in enhanced foam stability to drainage. Interestingly, the increased yield stress was attributed to increased particle elasticity at 3 wt% agar. Stability was provided through the fluid gel acting as a network of particles with a finite yield stress. Particles impeded the liquid flow in the foam, which resulted in the formation of localised plugs where particles were confined to foam channels. Examining the internal microstructure of this novel, exceedingly stable foam using X-ray tomography supported this mechanism.

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1. Introduction

The aeration of foods has important applications in a variety of products, from whipped cream to aerated chocolate. The presence of air reduces the calorific value and lowers the cost of foods whilst at the same time provides a luxurious texture that is desirable to the consumer. However, there is still a high percentage of fat in some whipped products. Due to the increasing consumer demand for low fat foods, there is a need to replace this fat with natural, readily available food ingredients. Hydrocolloid fluid gels provide a novel solution. Hydrocolloids are traditionally used as gelling or thickening agents in food products. However, the development of fluid gels has increased their functionality to fulfil a wider range of structural requirements (Cassin, Appelqvist, Normand, & Norton, 2000). A fluid gel is a suspension of gelled particles dispersed in a non-gelled continuous medium (Farrés, Moakes, & Norton, 2014; Garrec & Norton, 2012; Norton, Foster, & Brown, 1998). It is the colloidal nature of a fluid gel that allows them to mimic fat droplets

(Norton et al., 1998). These gelled particles could potentially stabilise foams not only by adsorbing at the air-water interface, but also by increasing local viscosity in the foam channels (Plateau borders and nodes) preventing liquid drainage. Lazidis et al. (2016) previously reported the improvement of foam stability by waxy protein gelled particles, which increased local bulk viscosity.

A foam can be considered a colloidal dispersion in which a gas, usually atmospheric air, is distributed throughout an aqueous continuous phase (Walstra, 2003). They are thermodynamically unstable systems that are constantly re-arranging to form lower energy structures (Murray & Ettelaie, 2004) and have considerably shorter lifetimes than other colloidal dispersions, such as emulsions. This is due to the higher surface tension of an air-water interface than oil-water (Dickinson, 2010). The mechanisms, which ultimately lead to the collapse of a foam, are: drainage, disproportionation and coalescence (Weaire, 1999). The intervening fluid between bubbles drains due to gravity, this results in the close approach of bubbles and eventually coalescence. In addition, disproportionation (the equivalent of Ostwald ripening in emulsions) is a further problem. Diffusion of gas occurs from smaller to larger bubbles due to the Laplace pressure difference (Ettelaie, Dickinson, Du, & Murray, 2003). As a result, smaller

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bubbles decrease in size whilst larger bubbles increase.

Foams are stabilised by surface-active molecules, which adsorb at the air-water interface and lower surface tension (Saint-Jalmes, 2006). Food foams are stabilised by a variety of surfactants including natural proteins from milk and egg, polar lipids such as monoglycerides and synthetic surfactants such as sorbitan esters (Kralova & Sjöblom, 2009). Food products are also stabilised by particles, for example whipped cream is stabilised by partially coalesced fat droplets (Dickinson, 2010). Most commonly, particles in foam systems provide stability by adsorbing at the air-water interface (Hunter, Pugh, Franks, & Jameson, 2008). A rigid film is formed which increases interfacial elasticity and viscosity, thus providing a barrier to drainage and coalescence. Particles made from most food-based materials are often not able to stabilise foams on their own, mostly due to limitations in size and hydrophobicity. However, previous research has shown that they can significantly aid foam stability (Lazidis, de Almeida Parizotto, Spyropoulos, & Norton, 2017). Particles can alternatively stabilise foams by remaining in the continuous phase and creating a weak gel network with a finite yield stress (Dickinson, Ettelaie, Kostakis, & Murray, 2004; Zúñiga & Aguilera, 2008). Particles hinder the liquid flow in the channels of the foam, which results in localised plugs where particles are confined to Plateau borders and nodes. Drainage is therefore reduced and foam stability is enhanced (Carn, Colin, Pitois, Vignes-Adler, & Backov, 2009; Friberg & Saito, 1976; Guignot, Faure, Vignes-Adler, & Pitois, 2010; Rio, Drenckhan, Salonen, & Langevin, 2014). Several studies have reported this non-classical arrest of drainage and emphasise its dependence on the yield stress of the foamed suspension (Gonzenbach, Studart, Tervoort, & Gauckler, 2006; Guillermic, Salonen, Emile, & Saint-Jalmes, 2009; Lesov, Tcholakova, & Denkov, 2014).

In this study, agar fluid gel systems were investigated for their potential as stabilised foams. The effect of added surfactant on fluid gel formation and properties upon storage was explored, along with processing conditions. Manufacture using a pin-stirrer produced fluid gels with advantageous particle shapes, which enhanced their functionality when aerated. The effect of agar concentration on the system was investigated. The effect of increasing polymer concentration in a fluid gel system is two fold. Firstly, increasing the concentration increases the volume fraction and therefore particle interaction (Garrec, Guthrie, & Norton, 2013; Norton, Jarvis, & Foster, 1999) and secondly, it increases the elasticity of the particles themselves (Frith, Garijo, Foster, & Norton, 2002).

2. Materials and methods

2.1. Materials

Agar and Tween 20 were obtained from Sigma Aldrich (UK). All concentrations were calculated as a weight percentage. Materials were used with no further purification or modification.

2.2. Preparation of agar fluid gels using a rheometer

The required mass of agar and 0.5 wt% Tween 20 was dispersed in deionised water heated to 90 °C, whilst stirring. Solutions were covered to minimise water evaporation. Fluid gels were produced in a rheometer using vane geometry (Kinexus, Malvern, UK). Aliquots of solution were transferred to the rheometer cup, pre-heated to 90 °C. The temperature was allowed to equilibrate for 5 min and was then decreased from 90 °C to 5 °C at a cooling rate of 2 °C min⁻¹, whilst the sample was under a shear rate of 500 s⁻¹. Each sample was prepared in triplicate and stored at 5 °C.

2.3. Preparation of agar fluid gels using pin-stirrer

Fluid gels for the application of foaming were prepared in a continuous process pin-stirrer as this allows larger scale production. The required mass of agar and 0.5 wt% Tween 20 was dispersed in deionised water heated to 90 °C, whilst stirring. The solution was then fed into the jacketed pin-stirrer cooled to 5 °C, through a peristaltic pump. 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 speed of the pump was set to 20 mL min⁻¹ to achieve a retention time of 7.5 min in the pin-stirrer resulting in a cooling rate of 8 °C min⁻¹. The shaft rotation speed was set to 1500 rpm as this has been previously reported by Gabriele, Spyropoulos, and Norton (2010) to give a narrow size distribution of particles. Fluid gels were stored at 5 °C.

2.4. Preparation of foams and determination of foam overrun

Equal volumes of fluid gels were whipped mechanically using a Hobart mixing unit at the highest speed setting for 5 min. The foaming ability of the systems was investigated by determining foam overrun (Equation (1)), measuring the amount of air incorporated into the system by weighing equivalent volumes of the original fluid gel sample and the sample after whipping. Experiments were carried out in three replicates.

$$\text{Overrun}(\%) = \left(\frac{m_{\text{fluid gel}}}{m_{\text{foam}}} \right) \times 100\% \quad (1)$$

2.5. Determination of foam half-life

The stability of the foams was determined using foam half-life measurements. The reduction of the foam height by half was recorded using a CCD camera and the half-life was later calculated. Experiments were carried out in three replicates.

2.6. Rheological methods

Rheological measurements were performed using a Kinexus rheometer (Malvern, UK) at 25 °C and 48 h after production, to ensure post-production particle ordering completion (Gabriele, Spyropoulos, & Norton, 2009; Garrec et al., 2013; de Carvalho & Djabourov, 1997). Viscosity curves were obtained by recording shear viscosity through a range of applied shear rates (0.001–500 s⁻¹). Amplitude sweeps were conducted at a frequency of 1 Hz as a function of applied oscillatory strain. A cone, with an angle of 4° and diameter of 40 mm, and plate geometry was used. To avoid slip a serrated parallel plate geometry was used (60 mm parallel plate and serrated bottom plate set at a 1 mm gap). Experiments were carried out in three replicates.

2.7. Surface tension measurements

Surface tension measurements of agar fluid gels produced in the pin-stirrer and later aerated were performed using a Kruss GmbH K100 tensiometer (Hamburg, Germany). The Wilhelmy plate method was used to measure static surface tension at an immersion depth of 2 mm for an equilibration time of 2400 s at 25 °C. Experiments were carried out in three replicates.

2.8. Imaging fluid gel particles

The phase contrast setting of an optical microscope (Leica

Microsystems, UK) was used to image fluid gel particles using objective lenses up to 20 \times magnification. Fluid gels were diluted with deionised water (1:4) and dropped onto a microscope slide with a coverslip.

2.9. Texture analysis

Quiescently cooled agar gels were stored at 5 °C for 48 h to ensure their exposure to the same conditions as fluid gels. Compression tests were completed using a TA XT plus Texture Analyser (Stable Micro Systems Ltd, UK). A 40 mm diameter cylindrical aluminium probe was used at a compression rate of 1 mm s⁻¹. Prepared samples of 21 mm in diameter and 10 mm in height were compressed to 50% strain and tests were carried out in three replicates. The force/distance data was converted to true strain (ϵ) and true stress (σ) in order to determine the initial modulus. This was calculated as the gradient of the region at 0–5% strain and relates to the stiffness/deformability of the gel matrix, until structure failure occurs (Bradbeer, Hancock, Spyropoulos, & Norton, 2014).

2.10. Micro computed tomography (Micro-CT)

Foam samples were scanned using a desktop X-ray micro-CT system (Skyscan 1172, Bruker, Belgium) at a voltage of 61 kV and current of 100 μ A. The radiograph images of each scan were reconstructed into 582 2D images using the Nrecon software and analysis was done using CTan software.

3. Results and discussion

3.1. Preparation and characterisation of agar fluid gels

Agar fluid gels were produced using a rheometer, as this method allows the kinetics of fluid gel formation to be monitored (Fig. 1). The viscosity increase was measured whilst cooling through the ordering and gelation temperature under an applied shear. The viscosity increased gradually as the temperature was decreased, until a sharp rise was observed at \approx 30 °C, indicating the beginning of gelation. Norton et al. (1999) described the formation of small gel nuclei, which upon further cooling continue to grow to an equilibrium particle size determined by the shear rate. The effect of shear rate on final fluid gel particle size has been previously studied by Gabriele (2011) and particle size was found not to significantly

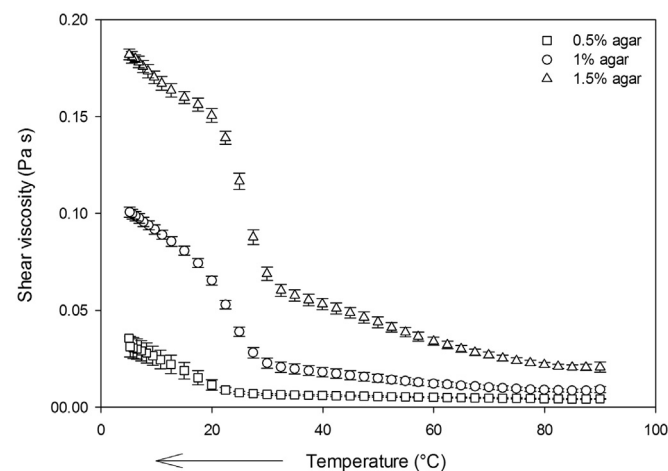


Fig. 1. Viscosity profiles during fluid gel production at 3 different agar concentrations.

change above a critical shear rate (and at the shear rates used in this study). Agar concentration, however, is a significant parameter and so its effect on fluid gel formation is evaluated here. From Fig. 1, the temperature of ordering can be observed to increase with agar concentration. This is a result of quicker gelation due to a higher number of particles (Norton et al., 1998). A higher concentration of agar therefore relates to a higher volume fraction and consequently increased viscosity.

The aim of this study was to produce fluid gels with the ability to be aerated. Therefore, a non-ionic surfactant, Tween 20, was incorporated into the fluid gels at a fixed concentration. Tween 20 has the highest water-solubility of all the Tweens and forms a mobile monomolecular layer when stabilising foams (Patino, Niño, & Gómez, 1997). The effect of incorporating this non-ionic surfactant into agar fluid gels at various agar concentrations was investigated (Table 1). Firstly, it is likely some Tween 20 was entrapped within the fluid gel particles, however, it has been reported that if interactions do occur between agar and non-ionic surfactants they are likely to be weak (Prasad, Siddhanta, Rakshit, Bhattacharya, & Ghosh, 2005). Secondly, gelation temperatures appear to decrease in the presence of Tween 20 (Table 1) however this is by less than 10% and is unlikely to be statistically different. A potential explanation is the effect of solvent quality, as the addition of Tween 20 leaves less water available for structuring. In addition, the viscosity of the agar fluid gels were measured after 48 h storage (Table 1) and the presence of Tween 20 did not appear to significantly affect their rheological behaviour. Furthermore, the material properties were investigated. The initial moduli of quiescently cooled gels at the same agar concentration were measured. The initial modulus reflects the stiffness/deformability of the gel matrix, until structure failure occurs (Bradbeer et al., 2014) and has been reported by Frith et al. (2002) to reflect the elasticity of the fluid gel particles themselves. The addition of Tween 20 did not significantly affect the initial moduli of quiescently cooled agar gels (Table 1) and is therefore inferred not to significantly affect the elasticity of agar fluid gel particles.

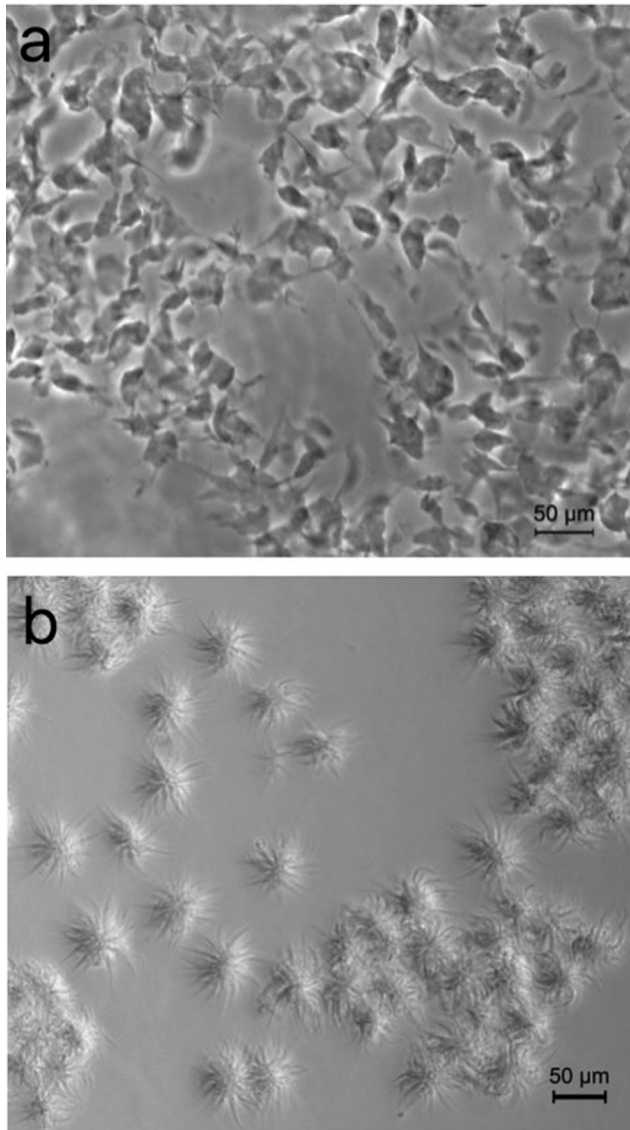
In order to produce larger quantities of fluid gel for aeration purposes, a continuous process pin-stirrer was used to manufacture fluid gels (described in Section 2.3). Production parameters were less easily controllable than in the rheometer set-up. The maximum rotational speed of 2000 rpm corresponds to \approx 200 s⁻¹ (Gabriele, 2011) and the cooling rate varied slightly depending on the inlet and outlet temperatures. However, suitable parameters were found which produced fluid gels with advantageous properties.

The conformation of gel particles is highly important as this directly affects foam stability. Fluid gels were therefore diluted and imaged using phase contrast microscopy. Agar fluid gels at 1 wt% agar produced by different methods are shown in Fig. 2. These micrographs show that particle shape was significantly affected by the production method. This trend was also observed for other concentrations of agar tested. Fluid gels produced using a vane geometry in the rheometer appeared as previously reported by Norton et al. (1999); individual “hairy” anisotropic particles (Fig. 2a). Agar fluid gels manufactured in the pin-stirrer, however, appeared as fibrous particles, which formed spherical structures with denser cores (Fig. 2b). The difference in particle shape occurred due to the effect of shear environments on the kinetics of gelation and consequently particle formation and shape. Fluid gel particles form through the growth of initial gel nuclei to an equilibrium particle size. Fluid gels produced on the pin-stirrer experienced a different shear profile, which resulted in the formation of small fibrous particles (due to fast gelation kinetics) that subsequently collided together in the flow to produce larger spherical structures. The shear environment experienced in the rheometer

Table 1

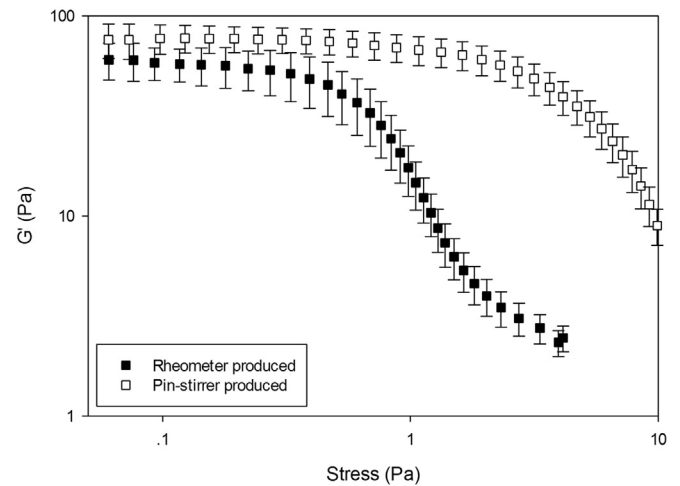
The effect of Tween 20 addition on the gelation temperatures and material properties upon storage of fluid gels at 3 different agar concentrations.

Concentration of agar (wt%)	Concentration of Tween 20 (wt%)	Gelation temperature ($^{\circ}\text{C}$)	Viscosity at 1 s^{-1} (Pa s)	Initial Modulus (kPa)
0.5	0	27.3 (± 0.3)	1.1 (± 0.0)	5.3 (± 0.5)
	0.5	25.2 (± 0.4)	0.9 (± 0.1)	5.1 (± 0.4)
1	0	31.7 (± 0.2)	1.7 (± 0.2)	30.7 (± 2.0)
	0.5	30.8 (± 0.3)	1.4 (± 0.0)	31.0 (± 4.4)
1.5	0	33.0 (± 0.2)	2.1 (± 0.1)	62.3 (± 5.3)
	0.5	32.3 (± 0.3)	1.9 (± 0.2)	66.6 (± 11.7)

**Fig. 2.** Micrographs of 1 wt% agar with Tween 20 fluid gels produced in (a) a rheometer with vane geometry and (b) in a pin-stirrer.

resulted in more segregated gel nuclei, which grew to a bigger, more spherical particle size.

In order to investigate how particle shape affected the interactions between particles, yield stress values were evaluated. These were determined from amplitude sweeps on a rheometer, as seen in Fig. 3. Yield stress was calculated as the stress required to decrease G' by 5% from the linear viscoelastic region (LVR). The yield stress of 1 wt% agar fluid gel prepared on the rheometer was $0.17 (\pm 0.06)$ Pa whilst on the pin-stirrer it was $0.63 (\pm 0.13)$ Pa. Fluid

**Fig. 3.** Storage modulus (G') as a function of stress during oscillatory strain sweeps of agar fluid gels produced on both the rheometer and pin-stirrer, 48 h after production. Yield stress is calculated as the stress required to decrease G' from the LVR by 5%.

gels manufactured on the pin-stirrer had higher yield stress values and, therefore, more particle interaction. It is thought that the branched nature of the particles caused them to interact to a higher extent than the more spherical, less branched rheometer made particles. Manufacture using the pin-stirrer provided a different shear profile that therefore resulted in kinetically trapping gelled regions into these novel-shaped particles, which resulted in enhanced particle interaction.

3.2. Rheological properties

The bulk viscosity of foams affect the mobility of the continuous phase and therefore drainage velocity (Saint-Jalmes, 2006). The viscosity profiles of agar fluid gel systems at various agar concentrations were measured (Fig. 4). All systems showed shear thinning behaviour as expected for interacting particulate systems (Saha & Bhattacharya, 2010). Unsurprisingly, shear viscosity increased upon raising agar concentration. However, viscosity profiles of fluid gels at 2.5 wt% and 3 wt% agar (coloured in grey in Fig. 4) overlapped; this suggests that a maximum packing fraction had been reached.

The viscoelastic behaviour of the fluid gel systems was assessed using oscillatory rheological data (Fig. 5). At each concentration, the storage modulus (G') dominated over the loss modulus (G'') which is indicative of interconnected structures (Ross-Murphy, 1994). G' increased with agar concentration due to an increase in volume fraction and particle elasticity (Garrec et al., 2013). The linear viscoelastic region (LVR) continued to a critical strain, where particle interactions were then disrupted. This causes the system to flow which can be seen by a decrease in G' (Fig. 6). The yield stress of fluid gels at different concentrations were determined from the strain sweeps as the stress required to decrease G' in the LVR by 5%

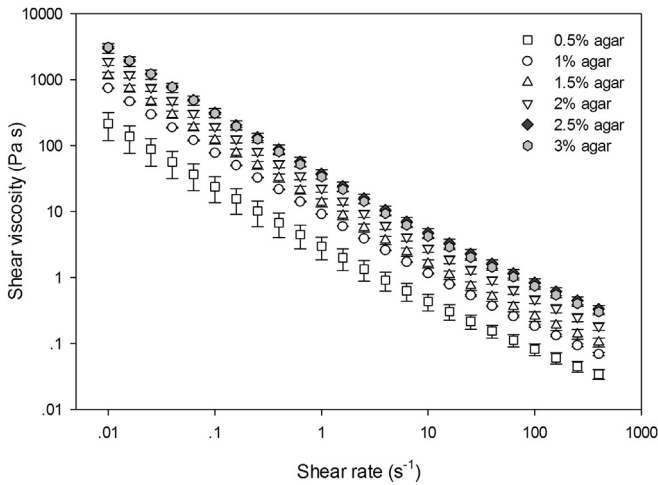


Fig. 4. Viscosity profiles of agar fluid gels produced at different concentrations, 48 h after production. The viscosity curves of 2.5 wt% and 3 wt% agar overlap and are therefore highlighted for clarity.

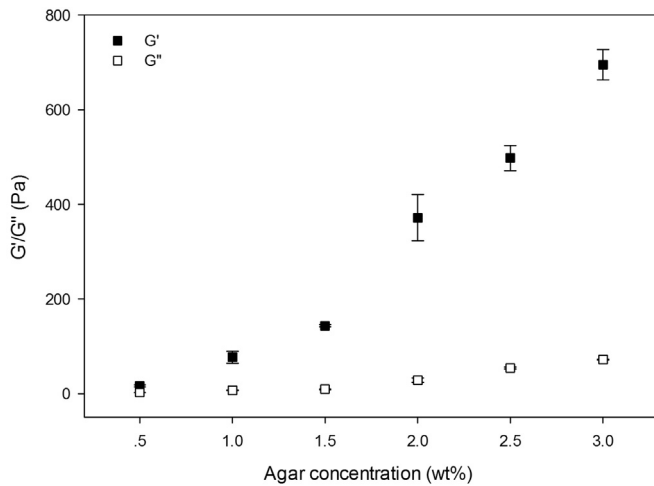


Fig. 5. Storage (G') and loss (G'') moduli as a function of applied oscillatory strain of agar fluid gels, 48 h after production.

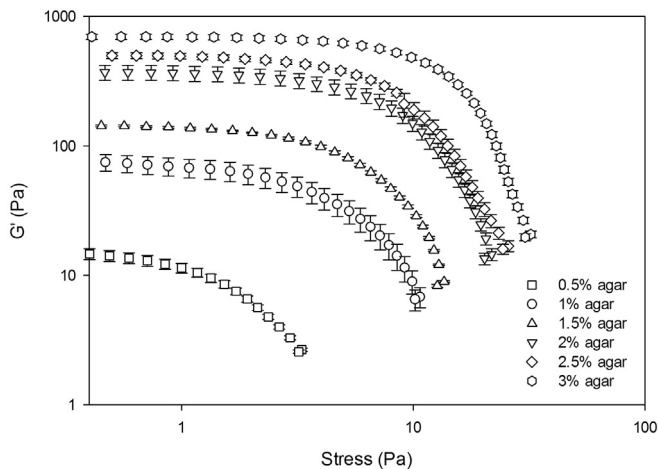


Fig. 6. Storage modulus as a function of stress during oscillatory strain sweeps of agar fluid gels, 48 h after production.

(Fig. 6). Yield stress increased with agar concentration due to enhanced particle interaction caused by higher phase volumes and an increase in particle stiffness (Garrec et al., 2013). Fluid gels at 2.5 wt% and 3 wt% agar still observed differences in their G' and yield stress despite their similar viscosity profiles, which had indicated a maximum packing fraction. G' increased from 498 (± 27) Pa at 2.5 wt% agar to 695 (± 32) Pa at 3 wt% agar and the yield stress increased from 2.0 (± 0.2) Pa to 3.3 (± 0.2) Pa (Fig. 6). This can therefore be attributed to the difference in particle elasticity; agar particles at 3 wt% were less deformable and so a greater stress was required to facilitate the movement of particles past one another and, hence, initiate flow.

3.3. Foaming capabilities

The functionality of agar fluid gel systems to produce stabilised foams was investigated. The ability of the systems to incorporate air was determined using foam overrun. Despite the reported difficulty of whipping air into particulate systems (Murray & Ettelaie, 2004), the soft elastic nature of the particles ensured foam overrun was high. Overrun was observed to decrease upon increasing agar concentration (Table 2). The surface tension of the fluid gels was similar at all agar concentrations (Table 2). This suggests that when aerated, Tween 20 saturates the air-water interface in all cases.

3.4. Foam stability mechanism

The foam stability at each concentration was assessed in terms of half-life measurements (Table 2). The addition of agar into the system (from 0 wt% to 0.5 wt% agar in Table 2) improved foam stability by a factor of eight. This was due to the presence of particles providing a mechanism of stability against drainage. Foams

Table 2
Foam properties of aerated fluid gels at various agar concentrations.

Agar concentration (wt%)	Surface tension after 2400 s (mN m^{-1})	Foam overrun (%)	Foam half-life (hours)
0	36.2 (± 0.15)	2045 (± 52)	1.0 (± 0.3)
0.5	39.3 (± 1.4)	1270 (± 27)	8.6 (± 1.6)
1	39.7 (± 1.5)	820 (± 28)	17.8 (± 2)
1.5	39.5 (± 0.9)	671 (± 13)	20.8 (± 0.5)
2.5	37.2 (± 1.7)	448 (± 61)	24.1 (± 1.9)
3	38.7 (± 2.4)	281 (± 37)	136 (± 13.9)

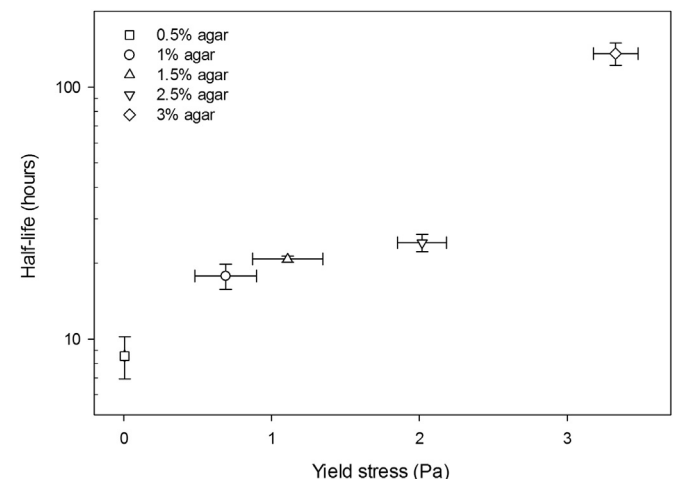


Fig. 7. Yield stress of agar fluid gels as a function of foam half-life.

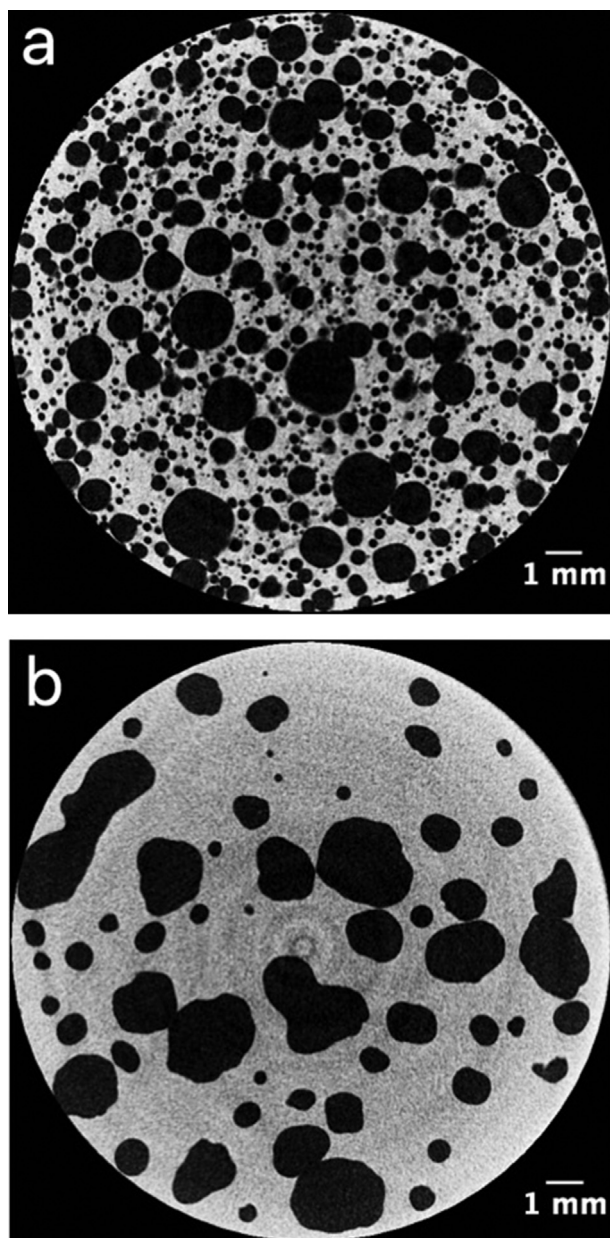


Fig. 8. Micro-CT images of aerated 3 wt% agar with Tween 20 fluid gel (a) 30 min after aeration and (b) 6 days after aeration.

produced at 0.5 wt% to 2.5 wt% agar exhibited a half-life of 24 h or less; stability was dramatically enhanced at 3 wt% agar, which displayed a half-life of six days. At this concentration, agar particles appeared to cease drainage for a considerable amount of time. Similar observations of particulate systems have been reported, where particles form a weak gel network, which results in a non-classical arrest of drainage. Several studies relate this to an increased yield stress of the foamed suspension. For example, [Guillermic et al. \(2009\)](#) showed that the yield stress of Laponite-stabilised foams increased upon suspension ageing, causing an enhanced stability of the foam to drainage. In addition, [Guignot et al. \(2010\)](#) described the retention of aggregated pyrogenic silica particles in foam channels due to the intrinsic yield stress of the system. Other studies reported a complete arrest of drainage at a system-specific threshold yield stress ([Gonzenbach et al., 2006](#); [Lesov et al., 2014](#)).

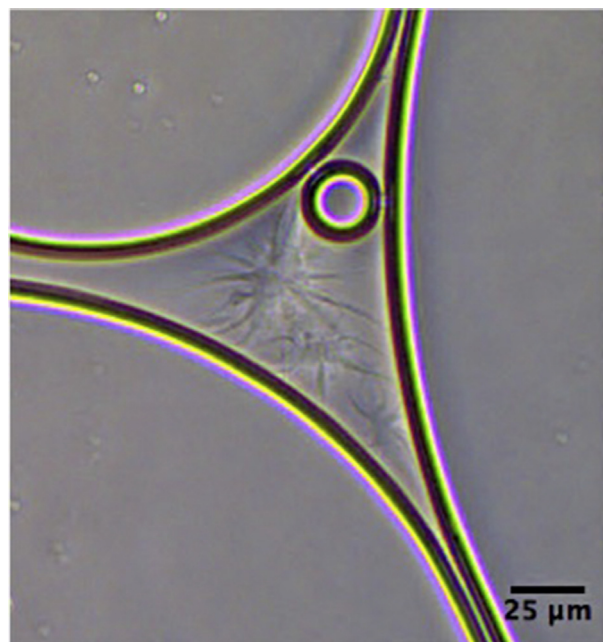


Fig. 9. Micrograph of a node formed from shaken 1 wt% agar with Tween 20 fluid gel with confined agar particles.

In order to investigate the mechanism of foam stability, rheological properties of the suspending fluid i.e. the fluid gel systems were therefore considered. As discussed in Section 3.1, manufacturing fluid gels using the pin-stirrer produced uniquely shaped particles that provided systems with high particle interaction. Increasing agar concentration, further increased particle interaction as well as particle elasticity. These effects were observed by an increase in system yield stress ([Fig. 6](#)). Foam half-life increased gradually from 0.5 wt% to 2.5 wt% agar until stability dramatically improved at 3 wt% agar. This behaviour was a result of the yield stress of the suspending fluid increasing to a critical point at 3 wt% agar ([Fig. 7](#)), which resulted in considerably slowed drainage. Agar fluid gels therefore provided stability when aerated through acting as a network of particles with a finite yield stress. Particles impeded the liquid flow in the foam through steric hindrance, which resulted in the formation of localised plugs ([Guignot et al., 2010](#)). Particles were subsequently confined to foam channels (Plateau borders and nodes) and as a result of fluid gel particle interaction providing the existence of a wider network, drainage was considerably slowed. The enhanced foam stability at 3 wt% agar can be attributed to increased particle elasticity (as discussed in Section 3.2) which was manipulated by increasing agar concentration whilst at the maximum packing fraction.

The advantage of a particulate gel system over weak gels is their ability to recover faster upon shear. Biopolymer gels at low concentrations can also reduce liquid drainage through possessing the required yield stress ([Blom et al., 2016](#)) however, most weak gels cannot recover upon shear. Gel particulate systems can therefore show benefits in some practical applications that require robust system performance upon shearing.

The microstructure of the aerated fluid gel at 3 wt% agar was investigated using X-ray tomography. [Fig. 8](#) shows a 2D slice of the foam 30 min after aeration (a) and six days after aeration (b) at the foam half-life. Both images were taken at the same cross-section. X-ray images probe the internal microstructure of the foam. The size of foam components such as air cells and foam channels can therefore be observed. Initial air cells were polydispersed; bubbles

ranged in size from $\approx 50 \mu\text{m}$ to 1.8 mm. The number of air cells had decreased greatly and their size increased when the foam reached its half-life, due to disproportionation and coarsening. Despite this high increase in air cell size, the foam was considerably stable. This highlights the importance of the particle “plugging” effect at slowing drainage, despite disproportionation. In addition, the Micro-CT images demonstrate that agar particles of $\approx 50 \mu\text{m}$ (Fig. 2b) could be confined to foam channels.¹ This was further supported in Fig. 9, where a sample of aerated 1 wt% agar fluid gel was observed using phase contrast microscopy. The video shows particles clearly confined to Plateau borders and nodes. It also illustrates the soft elastic nature of the particles through their movement around the air cells.¹

Supplementary video related to this article can be found at <http://dx.doi.org/10.1016/j.foodhyd.2017.06.038>.

4. Conclusions

Agar fluid gels have been shown to enhance foam stability and a strong dependence on the microrheology of the systems was found. Tween 20 was incorporated into agar fluid gels without affecting rheological and material properties but allowing foam production. Manufacturing these systems using a pin-stirrer produced novel particle shapes (a result of faster gelation kinetics) which increased particle interaction, indicated by yield stress. All systems showed good foaming properties. Foam stability was affected by the yield stress of the fluid gels, which was influenced by particle interaction and elasticity, manipulated by agar concentration. A substantial increase in stability was observed for systems from 2.5 wt% to 3 wt% agar. Both formulations had very similar viscosities; the increase in foam stability was therefore caused by an increase in particle elasticity. When 3 wt% agar particles were confined to foam channels during drainage, as well as being part of a greater network with a finite yield stress, they were less deformable and so provided a strong barrier to drainage.

This research has demonstrated that the use of fluid gels provides a novel solution to the increasing need to replace high levels of fat in food products with natural, readily available food ingredients. Agar fluid gels provide stability in foams, whilst also holding the potential to deliver desired textural properties of fat droplets. In addition, the properties of fluid gels can be further controlled and manipulated to meet additional requirements and further exciting applications.

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¹ This was further supported in Fig. 9, where a micrograph of a fluid gel shaken by hand shows agar particles of ≈ 25 – $50 \mu\text{m}$ confined to a node.