Heliyon 6 (2020) e05788

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of storage on the rheological and viscoelastic properties of mayonnaise emulsions of different oil droplet size

George Katsaros [*,1], Magdalini Tsoukala, Marianna Giannoglou [1], Petros Taoukis

Laboratory of Food Chemistry & Technology, School of Chemical Engineering, National Technical University of Athens, 5 Iroon Polytechniou Str., 15780, Greece

ARTICLE INFO

Keywords:
Mayonnaise emulsions
Rheology
Viscoelasticity
oil droplets size
Herschel Bulkley model
Cox Merz rule

ABSTRACT

The rheological and viscoelastic properties of mayonnaise emulsions with different size of oil droplets were investigated. A programmable rotational rheometer was used for the measurements and flow curves were determined at constant and variable shear rate. Mayonnaise exhibited a non-Newtonian, shear-thinning flow with yield stress and time-dependent features. The data from rotational tests were modeled by the Herschel-Bulkley equation. The temperature-dependence of η_a was modelled using the Arrhenius equation. Activation energy, E_a ranged from 15 to 20 kJ/mol. Viscoelastic properties were characterized using small amplitude oscillatory shear. Mayonnaise exhibited weak gel-like properties. The values of apparent and complex viscosity were correlated using the generalised Cox-Merz rule. According to the obtained values of parameter α, this rule could not be cut-down to one-parameter linear function. The rheological characteristics of mayonnaise were well correlated to the size of oil droplets.

1. Introduction

Mayonnaise is the most typical oil-in-water emulsion comprising 70–80% vegetable oil, pasteurized egg, vinegar, and spices (Code of Federal Regulations: 21CFR169.140) and represents more than 61% of the market share in terms of revenue and global consumption of dressing products (Technavio report, 2016). Mayonnaise rheological characteristics have been extensively studied. Several papers have been published regarding the flow properties of mayonnaise (Elliot and Ganz, 1977; Figoni and Shoemaker, 1983; Kiosseoglou and Sherman, 1983; Paredes et al., 1988, 1989; Yilmazer et al., 1991; Ma and Barbosa-Cánovas, 1995; Juszczak et al., 2003; Bengoechea et al., 2009; Laverse et al., 2012; Hakansson et al., 2016). Alternative thickeners and artificial emulsifiers that could be used, to produce a low-fat emulsion with similar rheological characteristics to the commercial full-fat counterparts have been researched (Juszczak et al., 2003; Chang et al., 2017; Primacella et al., 2019; Li et al., 2020). Novel technologies have also been proposed like High pressure processing (Aganovic et al., 2018).

Mayonnaise exhibits a non Newtonian, shear-thinning flow with yield stress and time-dependent features (Ma and Barbosa-Cánovas, 1995). The rheological properties of processed sauces, like mayonnaise, mustard, etc., can be modified by controlling the colloid mill gap during the preparation process (Aguilar et al., 1991). Colloid mills operate based on the principle of high-speed fluid shear and dispersed droplets of fine size, in the range of 3–5 μm (Perry and Green, 1997). Empirical textural index related to the viscoelasticity of the final products that depends on the colloid mill's gap is used in mayonnaise industry. As the colloid mill gap is increased, the size of the oil droplets increases, the thickness of the product decreases.

Small amplitude oscillatory shear (SAOS) is an index to characterize viscoelasticity of foods. When measuring SAOS, a sinusoidal oscillating strain (or stress) with an angular frequency "ω" is applied allowing for the measurement of the phase difference between stress and strain and of the amplitude ratio. This strain generates Two stress components are generated by this strain, the one elastic (elastic or storage modulus, G′) and one viscous component (viscous or loss modulus, G″) (Rao, 1999, 2014).

Magnitudes of G′ and G″ are influenced by frequency, temperature, and strain. For strain values within the linear range of deformation (as in this study), G′ and G″ are independent of strain. When G'>>G″, then the material bahaviour will be like a solid, meaning that the deformations will be essentially elastic or recoverable. However, if G''>>G′, the material's behavior is liquid-like (the energy used to deform the material is dissipated viscously) (Ferry, 1980).

* Corresponding author.
E-mail address: gkats@chemeng.ntua.gr (G. Katsaros).
[1] Current address: Institute of Technology of Agricultural Products, Hellenic Agricultural Organization-DEMETER, Sofokli Venizelou 1, Lykovrissi 14123, Greece.

https://doi.org/10.1016/j.heliyon.2020.e05788
Received 1 May 2020; Received in revised form 11 July 2020; Accepted 16 December 2020

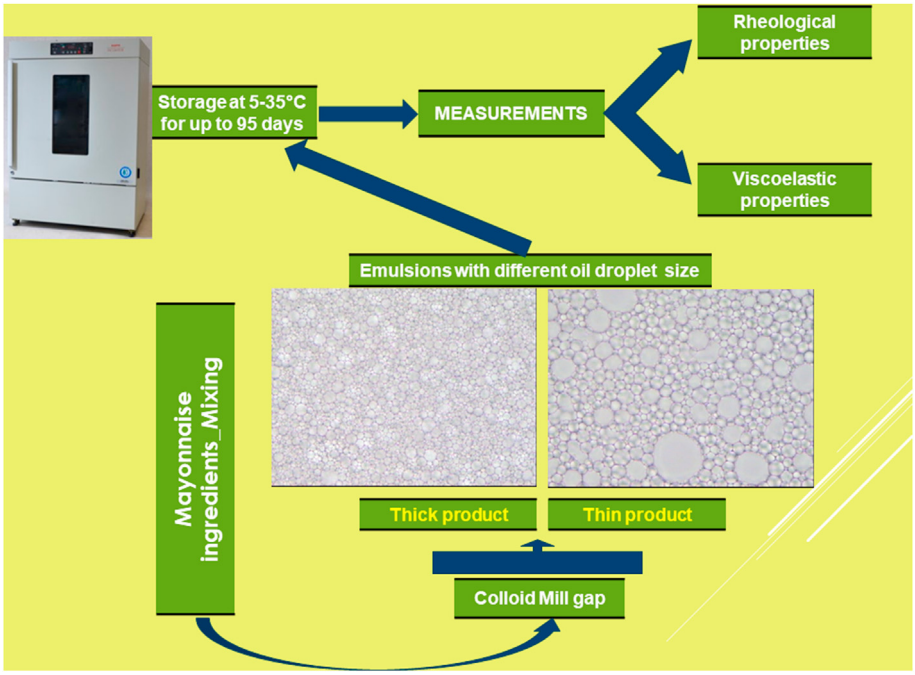

Figure 1. Graphical abstract.

The aims of this study were to characterize and study the effect of storage time and temperature on the rheological and viscoelastic properties of mayonnaise of different droplet size. There is a gap in the literature concerning the effect of storage time and temperature on the viscoelastic properties of that kind of products and our work targets towards this direction.

2. Materials and methods

Five samples of mayonnaise (Fat 76%, eggs and egg yolk 8.5%, Vinegar, salt, sugar, concentrated lemon juice, spices, antioxidant agent: Ethylenediaminetetraacetic acid calcium disodium salt, pH 4.1, a_w 0.925) with different viscoelastic properties were industrially prepared (produced by the industry following the typical production procedure, recipe and equipment-more details cannot be provided for confidentiality issues) by changing only the colloid mill's gap. The samples were produced considering the empirical value used in the mayonnaise industry to characterize their viscosity, the Plummet number (Pln) (in-house methodology followed from mayonnaise producers to quickly characterize their samples). Pln is the penetration depth (in cm) of an arrow-like metallic probe plummeting from specific height into the surface of a mayonnaise sample in a 500 mL beaker. The range of the Pln for the mayonnaises produced was selected to represent the range of thickness in commercial types of mayonnaise from thinner (increased Pln value-high penetration depth) to thicker emulsions (reduced Pln value-low penetration depth) (Figure 1). Pln was correlated to difficulty in penetration (necessary Force, N) by an arrow-like probe penetrating to a specific depth (4cm) into the surface of a mayonnaise sample in a 500 mL beaker using the Texture Analyser TA.XT2i (Stable Micro Systems Ltd, Godalming, UK) with P/40C conical probe, as a component.

2.1. Size of oil droplets

The size of oil droplets (ODS) was measured using a microscope Olympus CH 21502 (Olympus GmbH, Hanbury, Germany) with antocular lens 10X and objective lens 40X. By this method, the size of oil droplets under a microscope by preparing a monolayer on a slide is measured. Mayonnaise was placed on a slide and pressed lightly and carefully to form a layer of oil droplets surrounded by an aqueous phase, allowing for at least 15 oil droplets of different sizes measurement. The samples were coded as M1, M2, M3, M4 and M5, with M5 being the sample with the bigger oil droplets diameter and M1 the one with the smaller diameter, corresponding to the more viscous and the less viscous product, respectively.

2.2. Rheological properties

Rheological measurements were performed with a rotational rheometer Rheotec RC1 (Rheoteck, Messtechnik, Germany) with coaxial cylinders (rotor CC25-DIN Ti for cup CCB-25-DIN with inner diameter of 32mm). The data of the rheological measurements were analyzed with the supporting rheometer software. All experiments were conducted at 22 ± 0.2 °C.

The results obtained:

a. Flow curves with controlled shear rate (SR) at different storage times (1, 25, 45, 95 days) and at different storage temperatures (5 °C, ambient ~20 °C and 35 °C); the Controlled SR ranged from 3 to 1000 s^{-1} within 420 s. The Herschel–Bulkley model was applied to describe the results obtained.
b. Flow curves with controlled SR; the SR was built up from 1 to 1000 s^{-1} within 420 s and then back to 1 s^{-1} again, within another 420 s. The thixotropic hysteresis loop was determined.
c. Curves that show the shear stress time-dependent behavior from 0 to 30 min with a SR of 50 s^{-1}. The Weltman model was used to describe the obtained data (Rao, 1999).
d. Curves of apparent viscosity for temperature range 13–40 °C with constant SR at 100 s^{-1}. The Arrhenius equation was used to describe the obtained data (Equation 1).

$$\eta_a = \eta_{ref} \exp\left[\frac{E_a}{RT}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad \text{(Eq.1)}$$

where η_a depicts the apparent viscosity at specific SR, η_∞ depicts the frequency factor, E_a depicts the flow activation energy (J*mol^{-1}), R the gas constant (J*mol^{-1}*K^{-1}), T the temperature (K) and η_{ref} is the apparent viscosity at T_{ref}.

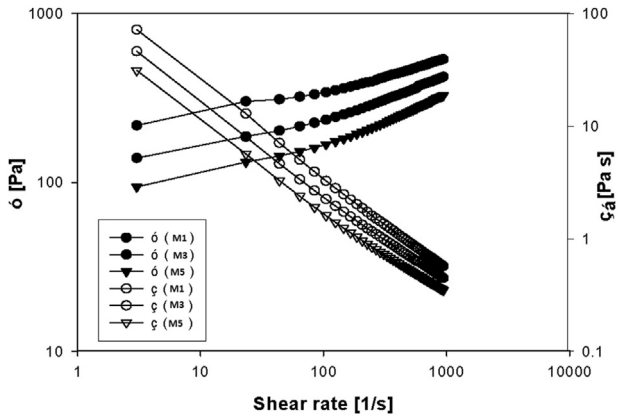

Figure 2. Flow curves of samples M1, M3 and M5.

2.3. Viscoelastic properties

Viscoelastic tests were conducted by a Texture Analyser (TA.XT2i, Stable Micro Systems Ltd, Godalming, UK) with Annular Pumping Rig, as a component. All the experiments were carried out at 22 ± 0.2 °C (using a cooling waterbath allowing for temperature control of the jacketed pumping rig). Mechanical spectra were planned for angular frequencies 3–63 rad/s at constant strain amplitude (0.1%).

Mechanical spectra were plotted for different storage times (1, 25, 45, 95 days) and storage temperatures (5 °C, ambient ~20 °C and 35 °C) to study their effect on the dynamic properties of mayonnaise. A preliminary test was performed by increase and decrease of angular frequency (ω) for the same mayonnaise.

The data were analyzed from a sine wave test, by dropping two anchors at 1/frequency period distant, using a macro. A cross-correlation routine then compared the Force, Time and Distance data. A number of parameters including the storage modulus (G′), the loss modulus (G″), the phase shift angle (δ) and the complex viscosity (η*) were calculated. The data then dropped into a Results spreadsheet. The values of apparent viscosity, η_a, and those of complex viscosity, η* (Bistany and Kokini, 1983; Gunasekaran and Ak, 2000; Rao and Tattiyakul, 1999) were correlated applying the generalized Cox-Merz rule (Equation 2).

$$\eta^*(\omega) = C[\eta_\alpha(\gamma)]^{\alpha}_{|\omega=\gamma} \quad \text{(Eq.2)}$$

where C and α were defined by experiments.

All the samples were left for 5–30 min after loading for relaxation and temperature equilibrium. Ten (10) min was selected as the rest time since the reproducibility was high. In the experiments all tests were duplicated and mean values were used for further analysis.

2.4. Statistical analysis

All the experiments were performed doubly, while all measurements were done in triplicates. One-way ANOVA was used to statistically process the data with a 95% significance level. The software used was Statistica 7 (Stat. Soft., Tulsa, OK, USA).

3. Results and discussion

3.1. Size of oil droplets

The macroscopic viscosity characterization of the emulsions tested was correlated to their microscopic characteristics, the size of their oil droplets (ODS). The diameter of the droplets as measured in the microscope ranged from 4.53 to 6.85 μm. The bigger the diameter of the oil droplets, the more viscous was the final product as evidenced by the macroscopic evaluation. The samples, depending on the ODS are coded as seen below:

- M1 is a mayonnaise with ODS equal to 4.53 μm and necessary force to penetrate the conical probe equal to 1.607 N
- M2 a mayonnaise of 4.76 μm and necessary force to penetrate the conical probe equal to 1.489 N
- M3 has ODS 5.34 μm and necessary force to penetrate the conical probe equal to 1.377 N
- M4 ODS was 6.02 μm and necessary force to penetrate the conical probe equal to 1.191 N
- M5 a mayonnaise of ODS equal to 6.85 μm and necessary force to penetrate the conical probe equal to 1.021 N.

3.2. Rheological properties

All tested mayonnaises appeared as non-Newtonian fluids with a shear-thinning flow with yield stress and time-dependent features (Ma and Barbosa-Cánovas, 1995). The flow curves of the mayonnaise with a CSR mode for M1, M3 and M5 are shown in Figure 2. The curves for M2 and M4 followed the trend of the other curves and fell between M1 and M3 (for M2 sample) and M3 and M5 (for M4 sample), respectively. The estimated parameters of the Herchel-Bulkley model are depicted in Table 1. The yield stress ranged from 85.20 to 193.38 Pa and decreased with oil droplets size (Table 1, Figure 3a). All the obtained results for "σ_0" were statistically different ($p < 0.05$) between them apart from M3 and M4 findings ($p > 0.05$), while for "n" values no statistical difference was observed ($p > 0.05$) among all samples. This decrease is attributed to a more compact format between the oil droplets. Elliot and Ganz (1977), Dickie and Kokini (1983), Ma and Barbosa-Cánovas (1995) studied the yield stress of mayonnaises available commercially and a very wide range of yield magnitude is reported. The consistency index (K) of sample varied from 8.48 to 25.82 Pa s^n (Table 1). All samples were characterized as pseudoplastic fluids since $n < 1$ (Table 1) (Paredes et al., 1989), and the n-value ranged from 0.38 to 0.49. The flow index (n), according to previous studies (Dickie and Kokini, 1983; Steffe, 1992), ranged between 0.13 and 0.91 for commercial or model mayonnaises mainly attributed to the variety of test methods and/or SR scale studied.

Sample M1 appeared to have the higher apparent viscosity values for the studied SR (Figure 2), and decreased values with oil droplets size (Figure 3c). As the oil droplets diameter increased, the mean distances

Table 1. Flow parameters of mayonnaise emulsions with ODS ranging from 4.53 to 6.85 μm.

Samples (ODS)	σ_0 [Pa]	K [Pa s^n]	n	R^2
M1 (ODS:4.53 μm)	193.38 ± 11.12^a	25.82 ± 1.21^a	0.38 ± 0.04^a	0.996
M2 (ODS:4.76 μm)	156.95 ± 10.72^b	23.22 ± 1.67^a	0.39 ± 0.03^a	0.999
M3 (ODS:5.34 μm)	118.36 ± 8.36^c	15.70 ± 0.92^b	0.43 ± 0.05^a	0.999
M4 (ODS:6.02 μm)	110.30 ± 10.18^c	11.10 ± 0.88^c	0.48 ± 0.05^a	0.998
M5 (ODS:6.85 μm)	85.20 ± 6.62^d	8.48 ± 0.99^d	0.49 ± 0.07^a	0.999

± represents the standard error of nonlinear regression analysis. Different superscript small letters indicate significantly different means ($p < 0.05$) within different lines.

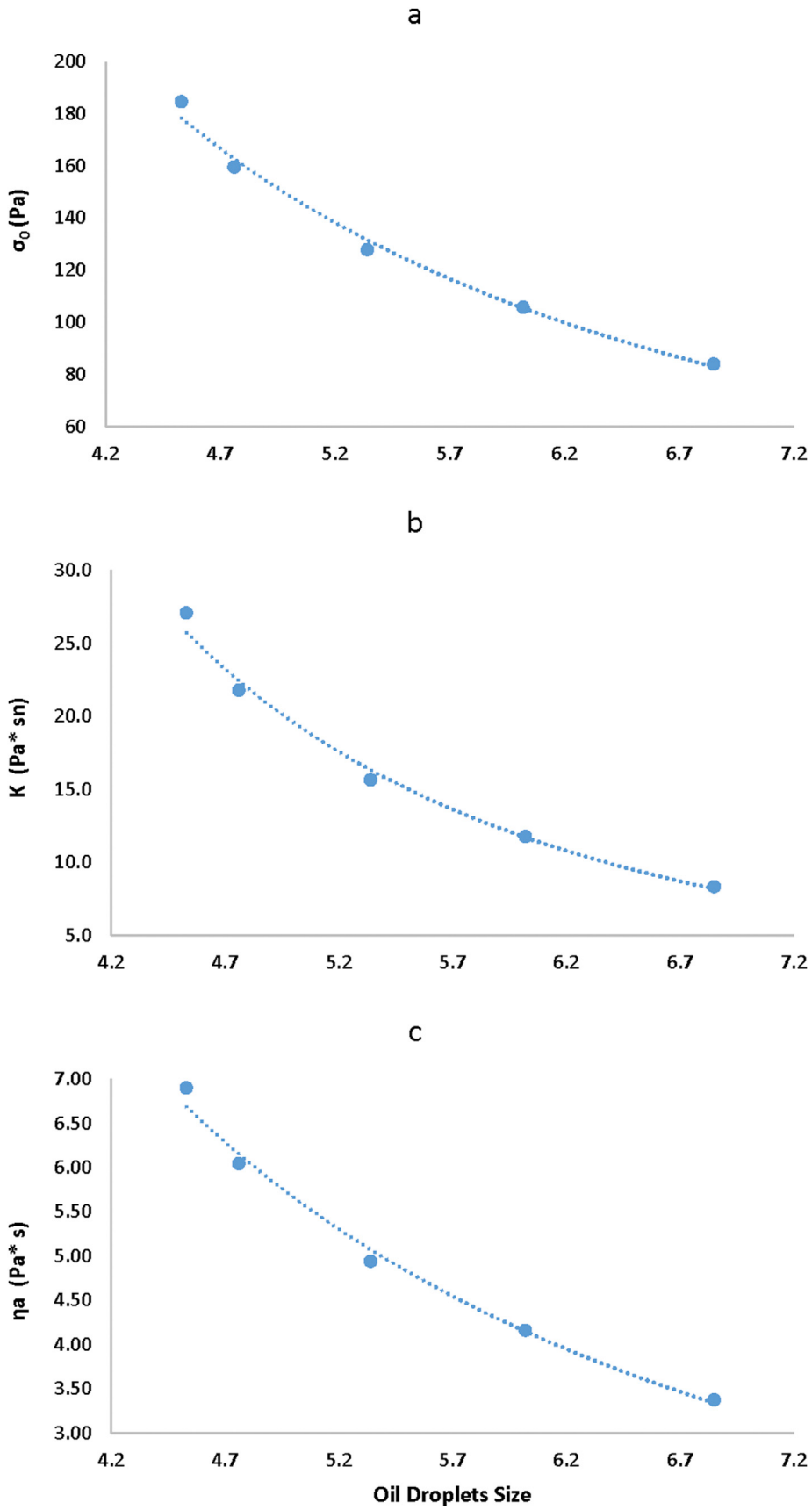

Figure 3. Correlation between σ_0 (a), K (b) and η_a (c) vs ODS at a shear rate equal to 64 s^{-1}

Table 2. Estimation of the Weltman model rheological parameters and of the area of thixotropic hysteresis loop.

Samples (ODS)	A [Pa]	B	R^2	S [Pa s^{-1}]
M1 (ODS:4.53 μm)	281.05	32.94	0.973	55796
M2 (ODS:4.76 μm)	280.01	26.33	0.997	39207
M3 (ODS:5.34 μm)	268.46	31.90	0.995	35358
M4 (ODS:6.02 μm)	201.06	19.54	0.991	29407
M5 (ODS:6.85 μm)	190.29	20.98	0.979	18269

Table 3. Apparent viscosity at 64 $s^{-1}$of mayonnaises M1-M5 with ODS ranging from 4.53 to 6.85 μm vs storage time at 20 °C.

Apparent Viscosity (Pa*s)					
Days of storage	M1 (ODS:4.53 μm)	M2 (ODS:4.76 μm)	M3 (ODS:5.34 μm)	M4 (ODS:6.02 μm)	M5 (ODS:6.85 μm)
1	7.09 ± 0.87[a]	4.29 ± 0.48[a]	3.36 ± 0.18[a]	3.01 ± 0.13[a]	2.38 ± 0.17[a]
25	5.58 ± 0.93[a]	3.80 ± 0.14[a]	3.04 ± 0.43[a]	2.73 ± 0.08[b]	2.06 ± 0.22[a]
45	5.33 ± 0.64[a]	3.39 ± 0.27[b]	3.53 ± 0.09[a]	2.54 ± 0.09[c]	1.96 ± 0.11[a]
95	4.37 ± 0.31[a]	3.41 ± 0.37[b]	3.43 ± 0.12[a]	2.39 ± 0.12[c]	2.75 ± 0.07[b]

± represents the standard error of nonlinear regression analysis. Different superscript small letters indicate significantly different means ($p < 0.05$) within different storage days.

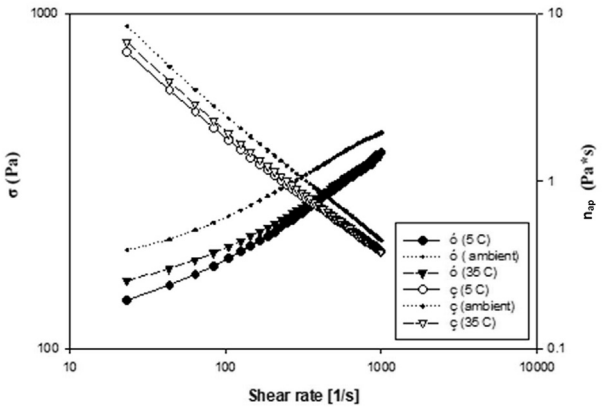

Figure 4. Effect of storage temperature on the flow curves of mayonnaise M3.

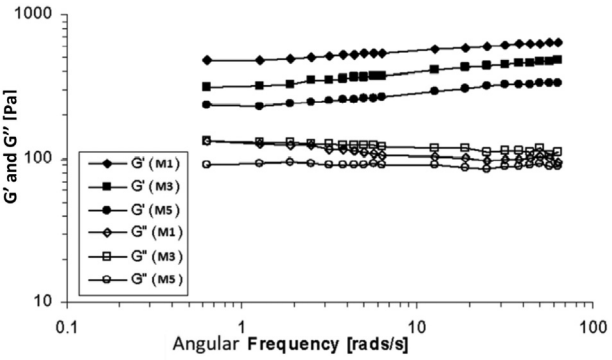

Figure 5. Storage modulus and loss modulus vs. frequency.

between them was greater and the interactions between them were less strong, leading in a viscosity loss.

The yield stress (σ_0), consistency index (K) and apparent viscosity (η_a) were modelled vs M-samples (Figs 3a-c) using power equations (Eqs. (3), (4), and (5)).

$$\sigma_0 = 2915.4*(ODS)^{-1.849}\ (R^2 = 0.98) \quad \text{(Eq.3)}$$

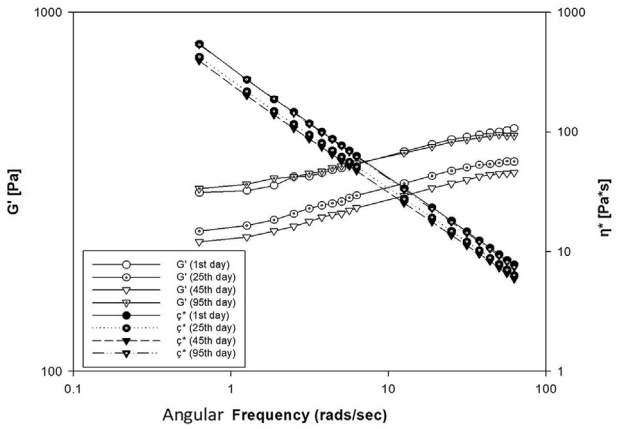

Figure 6. Effect of storage time on the dynamic properties of mayonnaise M3.

$$K = 1681.6*(ODS)^{-2.766}\ (R^2 = 0.99) \quad \text{(Eq.4)}$$

$$\eta_a = 84.6*(ODS)^{-1.68}\ (R^2 = 0.97) \quad \text{(Eq.5)}$$

All the tested mayonnaises showed a non-Newtonian, shear-thinning flow with yield stress and time-dependent features. The magnitude dependence to the shear of sample prior to and during filling in the viscometer (Rao, 1999, 2014) was taken into consideration. Mayonnaise M1 exhibited the highest thixotropy hysteresis loop, although decreased when ODS increased (Table 2). The generated data of shear stress vs. shear time at a SR equal to 50 s^{-1}, were described by the Weltman model, indicating thixotropic behavior (Paredes et al., 1988; Rao, 1999) and the model parameters were estimated (Table 2). The parameter A reflects the value of stress at t = 1s while B is the coefficient of thixotropic breakdown (related to the maximum area of thixotropic lag loop that showed each sample of mayonnaise).

3.2.1. *Effect of storage time on mayonnaise rheological properties*

A decrease of the yield stress for all mayonnaises (up to 37%) was observed during the first 45 days of storage at all temperatures. Further storage for 40 days caused an increase in the yield stress with higher absolute increase for the mayonnaise M1. This increase is attributed to a more compact and stable format. In Table 3 the values of apparent

Table 4. Dynamic parameters of sample M3 measured at a frequency of 0.63, 6.28, and 62.8 rads/sec as a function of storage time at 20 °C.

Days of storage	ω = 0.63 rads/sec				ω = 6.28 rads/sec				ω = 62.8 rads/sec			
	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)
1	$315.34^{a} \pm 15.25$	$133.36^{a} \pm 7.12$	$0.42^{a} \pm 0.05$	$544.92^{a} \pm 35.11$	$378.54^{a} \pm 18.55$	$63.27^{a} \pm 6.96$	$0.32^{a} \pm 0.01$	$63.27^{a} \pm 7.85$	$475.62^{a} \pm 41.22$	$109.74^{a} \pm 10.11$	$0.23^{a} \pm 0.01$	$7.77^{a} \pm 0.54$
25	$245.90^{b} \pm 18.72$	$103.81^{b} \pm 10.11$	$0.42^{a} \pm 0.02$	$424.80^{b} \pm 29.68$	$309.46^{b} \pm 19.85$	$51.52^{a} \pm 7.16$	$0.26^{b} \pm 0.02$	$51.52^{a} \pm 6.95$	$384.43^{b} \pm 37.15$	$99.16^{a} \pm 10.19$	$0.26^{a} \pm 0.02$	$6.32^{b} \pm 0.71$
45	$229.68^{b} \pm 11.41$	$89.33^{b} \pm 6.33$	$0.39^{a} \pm 0.03$	$392.22^{b} \pm 33.25$	$285.36^{b} \pm 11.75$	$47.33^{a} \pm 7.21$	$0.26^{b} \pm 0.03$	$47.33^{a} \pm 5.17$	$358.00^{b} \pm 24.22$	$93.39^{a} \pm 8.52$	$0.26^{a} \pm 0.02$	$5.89^{b} \pm 0.28$
95	$322.93^{c} \pm 20.31$	$101.05^{c} \pm 5.14$	$0.31^{a} \pm 0.02$	$538.54^{c} \pm 28.45$	$380.59^{c} \pm 14.25$	$91.26^{b} \pm 10.11$	$0.21^{b} \pm 0.02$	$62.29^{b} \pm 7.11$	$453.05^{c} \pm 21.23$	$93.66^{a} \pm 7.24$	$0.21^{a} \pm 0.03$	$7.36^{c} \pm 0.25$

± represents the standard error of nonlinear regression analysis. Different superscript small letters indicate significantly different means ($p < 0.05$) within different storage days.

viscosity (at shear rate 64 s^{-1}) for all M-samples mayonnaise emulsions stored at room temperature over time are presented. The values decreased vs storage time for all samples measured, nevertheless the statistical analysis showed that for M1 and M3 samples, no statistical differences were observed ($p < 0.05$) between all storage times studied. For samples M2, M4 and M5, statistically different ($p > 0.05$) values were observed after 45, 25 and 95 days, respectively.

3.2.2. *Effect of storage temperature on mayonnaise rheological properties*

For all samples, the storage temperature affected the flow curves of the mayonnaise, indicating that the structure of mayonnaise is significantly affected (Figure 4). The sample M1 stored at 35 °C showed increased value of parameter σ_0 (by 33%) and decreased value of consistency index (by 49%) compared to the other two temperatures. This is explained by the fact that although higher shear stress is required to initiate the mayonnaise flow, following which the shear stress is reduced. The yield stress increase is due to the fact that the proteins of mayonnaise are unfolded when temperature increases and wrap round the drops of oil creating a more compact network. The values of apparent viscosity of mayonnaise (at 64 s^{-1}) at 5 °C, 20 °C and 35 °C was measured and the results indicate reduced values when storage temperature increased (for M3, the corresponding values after storage for 45 days were 4.29, 3.80 and 3.39 for storage temperatures 5, 20 and 35 °C, respectively).

The temperature effect on mayonnaise viscosity for three samples (M1, M3 and M5) was studied and modelled by the Arrhenius equation. The Arrhenius parameters were estimated as 4.4, 4.4 and 4.6 Pa s for n_{ref} and 15.7, 15.5 and 20.5 kJ/mol for the E_a, for samples M1, M3 and M5, respectively. The activation energy values indicate that the viscosity of the larger droplet size mayonnaises sample (M5) exhibit a higher temperature dependence.

3.3. *Viscoelastic properties*

The mayonnaise viscoelasticity characteristics are attributed to a format among lipoproteins adsorbed all over oil droplets (Muñoz and Sherman, 1990). The results of the preliminary test revealed no structure alteration during the dynamic tests (Elliot and Ganz, 1977). In general, storage modulus, G′(ω) shows a noticeable plateau while loss modulus, G''(ω) is rather smaller compared to G′(ω) for solid-like gels (Almdal et al., 1993). In our study, the G′(ω) for all samples exhibited a pronounced plateau with G′(ω) > G''(ω) (Figure 5). According to the above definition, it could be accepted that the mayonnaise is a solid-like gel. The storage modulus and the complex viscosity of all samples were decreased with an increase of the ODS. The G and η* values were modelled vs ODS [$G' = 1984.1*(ODS)^{-1.10}$ ($R^2 = 0.98$) and $\eta^* = 302.6*(ODS)^{-1.04}$ ($R^2 = 0.98$)].

Other studies have shown that mayonnaise viscoelasticity is due to a network format, related to egg yolk proteins among interfaces of adjacent oil droplets (Kiosseoglou and Sherman, 1983).

The storage modulus (G′) (energy stored per cycle of deformation) of the samples showed a decrease in the first 45 days of storage and an increase after the 45 days (Figure 6). Increased G' values correspond to a solid-like mayonnaise (Ma and Barbosa-Cánovas, 1995). All the samples showed reduction in complex viscosity (η*), during the first 25 days of storage. After 45 days of storage, the complex viscosity increased for the samples M1, M2 and M3. The η* for the samples of higher ODS remained constant. The dynamic parameters for the sample M3 are listed in Table 4.

The G' (storage modulus) for the samples M1 and M3 remained constant. The mayonnaise M5 showed increased value of G ′ for storage temperature 35 °C, indicating that the particular sample is more sensitive in the change of temperature. The loss modulus (G″) presented fluctuations with the storage temperature. Table 5 lists the dynamic parameters for sample M1.

The complex and apparent viscosities were plotted vs frequency and SR (at ω = γ), respectively and were modelled by the generalized Cox-

Table 5. Dynamic parameters of sample M1 measured at a frequency of 0.63. 6.28. and 62.8 rads/sec as a function of storage temperature after 45 days of storage.

Storage temperature (℃)	ω = 0.63 rads/sec				ω = 6.28 rads/sec				ω = 62.8 rads/sec			
	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)	G' (Pa)	G'' (Pa)	tanδ	η* (Pa s)
5	$376.89^{a} \pm 34.21$	$117.51^{a} \pm 11.20$	$0.31^{a} \pm 0.01$	$628.32^{a} \pm 51.25$	$333.65^{a} \pm 25.11$	$102.81^{a} \pm 11.02$	$0.22^{a} \pm 0.02$	$73.37^{a} \pm 7.25$	$411.98^{a} \pm 57.29$	$98.12^{a} \pm 8.04$	$0.17^{a} \pm 0.01$	$8.55^{a} \pm 1.22$
ambient	$364.98^{a} \pm 18.45$	$95.54^{a} \pm 9.21$	$0.28^{a} \pm 0.02$	$629.53^{a} \pm 19.33$	$285.36^{a} \pm 34.29$	$83.80^{a} \pm 9.36$	$0.22^{a} \pm 0.02$	$72.72^{a} \pm 7.69$	$358.00^{a} \pm 47.21$	$93.39^{a} \pm 7.21$	$0.19^{a} \pm 0.03$	$8.63^{a} \pm 0.95$
35	$355.91^{a} \pm 25.21$	$136.38^{b} \pm 10.59$	$0.38^{b} \pm 0.04$	$606.62^{a} \pm 41.38$	$326.66^{a} \pm 21.33$	$98.58^{a} \pm 8.22$	$0.28^{b} \pm 0.03$	$75.52^{a} \pm 5.19$	$409.97^{a} \pm 54.10$	$101.62^{a} \pm 11.08$	$0.22^{a} \pm 0.02$	$8.82^{a} \pm 0.84$

± represents the standard error of nonlinear regression analysis. Different superscript small letters indicate significantly different means ($p < 0.05$) within different temperatures.

Table 6. Estimation of generalised Cox-Merz rule parameters for mayonnaises with ODS ranging from 4.53 to 6.85 μm.

Samples (ODS)	C	α	R^2
M1 (ODS:4.53 μm)	0.657	2.152	0.9996
M2 (ODS:4.76 μm)	0.351	2.329	0.9998
M3 (ODS:5.34 μm)	0.416	2.546	0.9995
M4 (ODS:6.02 μm)	0.166	2.554	0.9997
M5 (ODS:6.85 μm)	0.492	2.184	0.9998

Merz rule. The parameters of the model were estimated for all M-samples (Table 6). Parameter "a" varied from 2.152 to 2.554 (Table 6), indicating that the generalized Cox–Merz rule cut-down to one-parameter linear function is not applicable. The R^2 values showed that this rule could be applied for mayonnaises. Juszczak et al., (2004) used the Cox-Merz rule (two-parameter model) since the one-parameter equation could not be fitted to their data.

Similarly, the correlation of droplet size and linear viscoelasticity of the mayonnaises could be justified by a balance between shear induced coalescence and disruption of droplets, correlated to least possible droplet size and higher possible linear viscoelastic properties.

Maruyama et al. (2007) reported that the particle size data had negative and could be well correlated to hardness, fracturability, viscosity and adhesiveness, but not with sensory attributes. The findings demonstrate the strong relationship between particle size data and G' as evidenced by our results. The findings of Richardson et al. (1989) are also in agreement with our results, indicating that the noted solidity of the gels could be related to limited dynamic viscosity alterations than to extensive loss of shear viscosity.

4. Conclusions

Five mayonnaise samples with different rheological and viscoelastic properties were produced and their oil droplets size was measured and correlated to their viscoelasticity. All mayonnaise samples exhibited non-Newtonian, pseudoplastic behavior with yield stress. The apparent viscosity, consistency index, yield stress, storage modulus and complex viscosity values decreased with increasing droplet size and were mathematically described by power equations. Storage time and temperature affected the rheological and viscoelastic properties of mayonnaise. The G′(ω) of all samples exhibited a pronounced plateau with G′(ω) > G''(ω), indicating that mayonnaise is a solid-like gel. The storage modulus and the complex viscosity of all samples decreased with increased oil droplet size. For all samples, the storage temperature affected the flow curves of the mayonnaise, indicating that the structure of mayonnaise is significantly affected. The storage modulus (G′) of the samples showed a decrease in the first 45 days of storage and an increase after the 45 days, while the loss modulus (G″) presented fluctuations with the storage temperature.

Declarations

Author contribution statement

George Katsaros: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Magdalini Tsoukala: Performed the experiments; Wrote the paper.

Marianna Giannoglou: Analyzed and interpreted the data.

Petros Taoukis: Conceived and designed the experiments.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare the following conflict of interests: Dr. George Katsaros is member of the Advisory Board of Heliyon Food Science and Nutrition.

Additional information

No additional information is available for this paper.

References

Technavio Report, 2016. Global Food and Salad Dressings Market 2016-2020, July. SKU. IRTNTR9254.

Aganovic, K., Bindrich, U., Heinz, V., 2018. Ultra-high pressure homogenisation process for production of reduced fat mayonnaise with similar rheological characteristics as its full fat counterpart. Innovat. Food Sci. Emerg. Technol. 45, 208–214.

Aguilar, C., Rizvi, S.S.H., Ramirez, J.F., Inda, A., 1991. Rheological behavior of processed mustard. I. Effect of milling treatment. J. Texture Stud. 22, 59–84.

Almdal, K., Dyre, J., Hvidt, S., Kramer, O., 1993. Towards a phenomelogical definition of the term 'gel'. Polym. Gels Netw. 1, 5–18.

Bengoechea, C., López, M.L., Cordobés, F., Guerrero, A., 2009. Influence of semicontinuous processing on the rheology and droplet size distribution of mayonnaise-like emulsions. Food Sci. Technol. Int. 15 (4), 367–373.

Bistany, K.L., Kokini, J.L., 1983. Dynamic viscoelastic properties of foods in texture control. J. Rheol. 27, 605–620.

Chang, Cuihua, Li, Junhua, Li, Xin, Wang, Chenying, Yang, Yanjun, 2017. Effect of protein microparticle and pectin on properties of light mayonnaise. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 821, 8–14.

Code of Federal Regulations, FOOD and DRUGS, *Subpart B–Requirements For Specific Standardized Food Dressings And Flavorings*, Title 21, Volume 2, Sec. 21CFR169.140_ Mayonnaise.

Dickie, A.M., Kokini, J.L., 1983. An improved model for Food thickness from non-Newtonian fliud mechanics in the mouth. J. Food Sci. 48, 57–61, 65.

Elliot, J.H., Ganz, A.J., 1977. Salad dressings-preliminary rheological characterization. J. Texture Stud. 8, 359–371.

Ferry, J.D., 1980. Viscoelastic Properties of Polymers, third ed. John Wiley and Sons, New York.

Figoni, P.I., Shoemaker, C.F., 1983. Characterization of time dependent flow properties of mayonnaise under steady shear. J. Texture Stud. 14, 431–442.

Gunasekaran, S., Ak, M.M., 2000. Dynamic oscillatory shear testing of foods-selected applications. Trends Food Sci. Technol. 11, 115–127.

Håkansson, A., Chaudhry, Z., Innings, F., 2016. Model emulsions to study the mechanism of industrial mayonnaise emulsification. Food Bioprod. Process. 98, 189–195.

Juszczak, L., Fortuna, T., Kośla, A., 2003. Sensory and rheological properties of Polish commercial mayonnaise. FoodNahrung 47 (4), 232–235.

Juszczak, L., Witczak, M., Fortuna, T., Banyś, A., 2004. Rheological properties of commercial mustards. J. Food Eng. 63 (2), 209–217.

Kiosseoglou, V.D., Sherman, P., 1983. Influence of egg yolk lipoproteins on the rheology and stability of o/w emulsions and mayonnaise.I. Viscoelasticity of groundunt oil-in-water emulsions and mayonnaise. J. Texture Stud. 14, 397–417.

Laverse, J., Mastromatteo, M., Frisullo, P., Del Nobile, M.A., 2012. X-ray microtomography to study the microstructure of mayonnaise. J. Food Eng. 108, 225–231.

Li, Anqi, Gong, Tian, Hou, Yanjie, Yang, Xi, Guo, Yurong, 2020. Alginate-stabilized thixotropic emulsion gels and their applications in fabrication of low-fat mayonnaise alternatives. Int. J. Biol. Macromol. 1461, 821–831.

Ma, L., Barbosa-Cánovas, G.V., 1995. Rheological characterization of mayonnaise. Part II: flow and viscoelastic properties at different oil and xanthan gum concentrations. J. Food Eng. 25, 409–425.

Maruyama, K., Sakashita, T., Hagura, Y., Suzuki, K., 2007. Relationship between rheology, particle size and texture of mayonnaise. Food Sci. Technol. Res. 13 (1), 1–6.

Muñoz, J., Sherman, P., 1990. Dynamic viscoelastic properties of some commercial salad dressings. J. Texture Stud. 21, 411–426.

Paredes, M.D.C., Rao, M.A., Bourne, M.C., 1988. Rheological characterization of salad dressings. I. Steady shear, thixotropy and effect of temperature. J. Texture Stud. 19, 247–258.

Paredes, M.D.C., Rao, M.A., Bourne, M.C., 1989. Rheological characterization of salad dressings. II. Effect of Storage. J. Texture Stud. 20, 235–250.

Perry, R.H., Green, D.W., 1997. Perry's Chemical Engineers' Handbook, seventh ed. McGraw-Hill, New York, p. 13. Chapter 20.

Primacella, M., Wang, T., Acevedo, N.C., 2019. Characterization of mayonnaise properties prepared using frozen-thawed egg yolk treated with hydrolyzed egg yolk proteins as anti-gelator. Food Hydrocolloids 96, 529–536.

Rao, M.A., 1999. Rheology of Fluid and Semisolid Foods. Principles and Applications. Aspen Publishers, Inc, Gaithesburg, Maryland.

Rao, M.A., 2014. Rheology of Fluid, Semisolid, and Solid Foods. Principles and Applications. SPRINGER.

Rao, M.A., Tattiyakul, J., 1999. Granule size and Rheological behavior of heated tapioca starch dispersions. Carbohydr. Polym. 38, 123–132.

Richardson, R.K., Morris, E.R., Ross-Murphy, S.B., Taylor, L.J., Dea, I.C.M., 1989. Characterization of the perceived texture of thickened systems by dynamic viscosity measurements. Food Hydrocolloids 3, 175–191.

Steffe, J.F., 1992. Yield stress: phenomena and measurement. In: Singh, R.P., Wirakartakusumah, M.A. (Eds.), Advances in Food Engineering. CRC Press, London, p. 363. Ch. 29.

Yilmazer, G., Carrillo, A.R., Kokini, J.L., 1991. Effect of propylene glycol alginate and xanthan gum on stability of O/W emulsions. J. Food Sci. 56 (2), 513–517.