https://doi.org/10.17113/ftb.64.02.26.9220 original scientific paper

Impact of Egg Components on Model Pasta Dough Rheology, Microstructure, and Mechanical Dough Rolling Energy

Running head: Egg Pasta Dough Rheology and Rolling Process

Berkay Berk[1], Şelale Öncü Glaue[2] and Sevcan Ünlütürk[1*]

[1]Department of Food Engineering, Faculty of Engineering, Izmir Institute of Technology, İzmir, Türkiye
[2]Food Processing Department, Efes Vocational School, Dokuz Eylül University, İzmir, Türkiye

Received: 6 June 2025
Accepted: 7 December 2025

SUMMARY

Research background. Pasta is a widely consumed food usually made from durum wheat semolina. During production of pasta, pasta dough kneading is the first step and there are varying levels of deformation that are applied to the dough. All these deformations are related to the rheological properties of the pasta dough. The rheological properties of pasta dough are affected from its ingredients.

Experimental approach. In this study, three different types of model pasta dough were prepared using water, whole eggs, or egg yolks. To evaluate their properties, linear, non-linear (LAOS) and extensional rheological tests were conducted. The energy requirement during dough rolling process was linked to the rheological properties of the dough samples.

[*]Corresponding author:
Phone: +902327506906
Fax: +902327506196
E-mail: sevcanunluturk@iyte.edu.tr

Results and conclusions. Results showed that the energy requirement during rolling is strongly correlated with crossover strain, oscillatory viscoelastic moduli, creep-recovery compliances and extensional consistency coefficient. The addition of whole egg and egg yolk increased the rigidity of the model dough (Plain: 6.32 kPa, Whole: 28.48 kPa and Yolk: 117.05 kPa Young's Modulus). The work done during rolling increased with addition of egg (Plain: 15.19 J, Whole: 27.14 J and Yolk: 33.02 J). After rolling, samples were cut, cooked, and the microstructure was evaluated. The effect of egg constituents on the microstructure was observed as a lipid-coated smoother surface and strong formation of a protein network.

Novelty and scientific contribution. This study provides a comprehensive rheological characterization of model pasta doughs formulated with different egg constituents using linear, nonlinear, and extensional tests. By linking these rheological properties to the mechanical energy required during rolling, the work introduces a novel approach to quantitatively predict processing behaviour from fundamental dough mechanics. The findings also highlight how egg yolk significantly enhances dough rigidity and alters microstructure, contributing to improved understanding of ingredient-function relationships in pasta formulation.

Keywords: egg; pasta dough; linear rheology; non-linear rheology; extensional rheology; rolling

INTRODUCTION

Cereals and their products are major staples in global diets. Pasta is a type of cereal product. Pasta dough is prepared by kneading the durum wheat (*Triticum durum*) semolina or flour with water. Once the durum flour reaches the required moisture level, it is added to a mixer, where homogenization is performed under high pressure. The homogenized dough is then kneaded again under vacuum to remove air bubbles and extruded into the desired shape before the drying process.

After hydrating the durum flour, the kneading and shaping stages take place and the rheology of the dough significantly influences the process parameters such as rolling force, torque and energy consumption. During mixing and shaping, the dough undergoes deformation up to 500 % (*1*). A significant deformation aids in developing the dough by breaking and reforming physical bonds. Proper dough development influences the shaping and subsequent drying processes. Dough preparation conditions, and the ingredients used also have a significant impact on the dough's physical properties.

Numerous studies have shown that the various agents and their amounts added to the dough have significant effects on dough rheology. For example, Li *et al.* (*2*) analysed the rheological properties of pasta dough, gluten gel, and gels made from different gluten fractions through a stress relaxation test. The study demonstrated how the gluten fractions of wheat affected the dough's rheological properties. Larrosa *et al.* (*3*) made gluten-free pasta dough from corn flour and starch using an egg and obtained desirable dough consistency through the egg's binding effect.

During rolling of the pasta dough, the deformations are observed by biaxial extensional strain. There are several studies discussing the effect of ingredients on biaxial extensional properties of the dough. In the study of Dufour *et al.* (*4*), extensional rheological properties as affected by water content of the and mixing time of the dough were discussed. The findings of the study revealed that both water and the mixing affected the gluten network structure by leveraging the protein strands resulting in increased extensional consistency. In another study conducted by Yang *et al.* (*5*), the variations in deformation by different methods of dough kneading were investigated using extensional rheology. They found out the best gluten alignment was achieved by single direction pressing and bidirectional rolling due to arrangement of the protein strands that were subjected to external force.

In this study, three different pasta dough samples were prepared using water, whole egg, and egg yolk components. The rheological properties of the dough were analysed and related to the technological properties of pasta dough rolling process. To achieve this, the study investigated the following: 1) linear viscoelastic properties, 2) nonlinear viscoelastic properties, 3) extensional rheological properties of the pasta dough, 4) parameters of the dough rolling process, and 5) quality characteristics of the finished pasta.

MATERIALS AND METHODS

Materials

The flour used in this study is made from *Triticum durum* (Tellioğlu Gıda, Balıkesir, Türkiye), having 0.7 g fat, 71 g carbohydrate, 12.5 g protein, and 0.62 g ash, and 15.18 g moisture in 100 g flour. Mean particle size of the flour used was (82.99±1.93) µm. To prepare the dough samples, distilled water, whole egg, and egg yolk were used, separately. The egg was purchased from a local market in İzmir, Türkiye. The moisture content of egg components was determined to be 49.57±2.13 % (*m*/*m*) for egg yolk and (90.47±1.89) % (*m*/*m*) for egg albumen. The yolk-to-albumen ratio of the eggs was measured as (43.60±3.20) % (*m*/*m*). The soluble protein content of the egg constituents was determined by the Bradford method (*6*). The results indicated that the protein concentration was (0.23±0.03) g of protein per gram of dry solid for egg yolk, while for egg albumen, it was (0.79±0.09) g of protein per gram of dry solid. The lipid content of egg yolk was measured according to the method of Lin *et al.* (*7*) and found to be (36.20±1.21) % (*m*/*m*).

Model pasta dough preparation

In this study, three different dough samples were prepared with water, whole egg, and egg yolk, separately. In all formulations, 100 g of flour was mixed with 50 g of liquid substance, which could be either water, a whole egg, or egg yolk. The amount of the liquid substances was kept at the lowest, considering the operating conditions of the equipment used. The kneading process was done using a food mixer (Bosch MUM5, Gerlingen, Baden-Württemberg, Germany) with a kneading hook (Bosch, Item Nr. 080060, Gerlingen, Baden-Württemberg, Germany) at speed 4 (60 rpm) for 5 min.

Rheological analyses

All rheological measurements were performed immediately after kneading the dough using DHR-20 Rheometer (TA Instruments, New Castle, DE, USA) with a 50 mm parallel plate equipped with a Peltier system. The measurements were performed at 25 °C, and the lateral edge of the dough was covered with paraffin oil to prevent moisture loss during experimentation.

Strain sweep test

To determine linear (LVR) and non-linear viscoelastic region, strain sweep test was performed. From 0.01 to 100 % strain was swept at 10 rad/s oscillatory frequency. The measurement gap was set to 2 mm, and the axial force was waited to relax under 10 N prior to measurement.

Frequency sweep test

In LVR, a frequency sweep test was conducted at 0.02 % strain in between 0.1 and 10 rad/s. The measurement gap was set to 2 mm, and the axial force was waited to relax under 10 N prior to measurement. The storage (*G*') and loss (*G*") moduli and complex viscosity (η^*) were modeled using power law models given in Eqs. 1 and 2 (*8*).

$$G' = K'\omega^{n'} \quad /1/$$

$$G'' = K''\omega^{n''} \quad /2/$$

where *K*' and *K*" are consistency indices ($\mathrm{Pa \cdot s^{n'}}$ and $\mathrm{Pa \cdot s^{n''}}$, respectively) and *n*' and *n*" are oscillatory flow behaviour indices of storage and loss moduli, respectively.

Creep-recovery test

The creep-recovery test was performed under constant stress (σ_0) of 200 Pa for the creep period and 0 Pa for the recovery period with a 2 mm gap height. The duration for the creep and recovery periods was 120 and 180 s, respectively. Then, the strain data was converted to creep compliance ($J_c(t)$) and recovery compliance ($J_r(t)$).

$J_c(t)$ data were modeled with the 6-element Burgers (1 Maxwell and 2 Kelvin-Voight models in series) model in Eq. 3 (*8*).

$$J_c = J_{c,0} + J_{c,1}\left(1 - e^{-\frac{t}{\lambda_{c,1}}}\right) + J_{c,2}\left(1 - e^{-\frac{t}{\lambda_{c,2}}}\right) + \frac{t}{\mu_{c,0}} \quad /3/$$

where $J_{c,0}$ is instantaneous compliance (Pa^{-1}), $J_{c,1}$ is 1st element retarded compliance (Pa^{-1}) , $\lambda_{c,1}$ is 1st element retardation time (s), $J_{c,2}$ is 2nd element retarded compliance (Pa^{-1}) , $\lambda_{c,2}$ is 2nd element retardation time (s) and $\mu_{c,0}$ is zero shear viscosity ($\mathrm{Pa} \cdot \mathrm{s}$) of the free dashpot.

$J_r(t)$ data were modeled with the 6-element Burgers (1 Maxwell and 2 Kelvin-Voight models in series) model in Eq. 4 (*8*).

$$J_r = J_{r,0} + J_{r,1}e^{-\frac{t}{\lambda_{r,1}}} + J_{r,2}e^{-\frac{t}{\lambda_{r,2}}} + \frac{t}{\mu_{r,0}} \quad /4/$$

where $J_{r,0}$ is instantaneous recovery compliance (Pa^{-1}), $J_{r,1}$ is 1st element retarded recovery compliance (Pa^{-1}) , $\lambda_{r,1}$ is 1st element recovery retardation time (s), $J_{r,2}$ is 2nd element retarded recovery compliance (Pa^{-1}) , $\lambda_{r,2}$ is 2nd element recovery retardation time (s) and $\mu_{r,0}$ is zero shear viscosity ($\mathrm{Pa} \cdot \mathrm{s}$) of the free dashpot.

Large amplitude oscillatory shear (LAOS) analysis

LAOS properties of the dough samples were acquired beyond the LVR part (*9*). The data collected were processed using MITlaos software (*10*). From the data, non-linear measures ($G'_L, \eta'_L, S, and\ T$) and Lissajous-Bowditch curves obtained.

Extensional rheology

Biaxial extensional rheology measurements were conducted in the compression mode of the rheometer with $1.667 \cdot 10^{-5}$ m/s compression speed, 25 mm sample diameter and 10 mm height. A constant volume approach was followed, and the upper and lower plates were lubricated with paraffin oil. Biaxial extensional stress vs. extensional strain rate data were obtained. Young's modulus (YM) was calculated in the LVR part using the slope of the stress-strain curve. Biaxial extensional viscosity vs. extensional strain rate data were fitted to Power-Law model using Eq. 5 (*8*).

$$\eta_B = K_B \dot{\varepsilon}^{n_B - 1} \quad /5/$$

where η_B is biaxial extensional viscosity (Pa·s), K_B is Power-Law constant (Pa·s^{nB}) and n_B is extensional thinning index. Maximum extensional strain rate ($\dot{\varepsilon}_{b,max}$) was kept low (0.24 s^{-1}) to prevent lubricant loss.

Dough rolling process

The kneaded dough samples were hand rolled to 5 mm thickness before machine rolling, then cut into 10 cm×10 cm square. A digital ammeter (CEM DT-9987, Shenzhen, China) was serially connected to pasta rolling machine (roller diameter: 2.5 cm) (Atlas Marcato 150, Campodarsego, Italy). While rolling with a roller gap of 2 mm (no: 3), current measurement was performed in AC mode and time vs current data was acquired. The roller speed and the operating voltage are recorded as 60 rpm, and 230 V, respectively. The angular impulse can be defined as the area under the torque vs time curve (*11*). The work done by the rollers can be estimated by Eq. 6 (*11*).

$$W = j \times \omega \left(\frac{rad}{s}\right) \qquad /6/$$

where *W* is work done (J) and *j* is angular impulse (N·m·s). When the rotational speed in terms of rad/s (that is 6.28 rad/s) is multiplied by the *j*, total work done to roll the dough is obtained.

Microstructure of the raw and cooked pasta

Cut dough samples were subjected to drying before and after cooking in a laboratory oven (P Select Incudigit, Spain) at 50 °C and 15 % relative humidity for 24 h. Convection mode was not used to prevent rapid drying and surface cracks. Then, 10 g of each dried sample was cooked in 100 mL boiling distilled water for 5 min. The cross-sectional morphologies of dried pasta dough before and after cooking were examined by using a scanning electron microscope (SEM, 250 Quanta FEG, FEI Company, Hillsboro, Oregon, USA) at magnification rates of 500 and 2,500×. Samples were gold-coated with a sputter coater (Emitech K550X, Quorum Technologies Inc., East Sussex, UK) under 10 mA for 30 s.

Statistical analysis

All formulations were prepared twice, and analyses were conducted in duplicate and the differences in the samples were tested using analysis of variances (ANOVA) with Tukey comparison test at 95 % confidence level. The relation between rheological properties and energy required for dough rolling were investigated using Pearson correlation test at 95 % confidence level. The analyses were conducted using Minitab statistical software (*12*).

RESULTS AND DISCUSSION

Rheological analyses of pasta dough

Linear viscoelastic properties

Strain sweep test was conducted to determine the linear viscoelastic region, and the strain sweep profiles of pasta doughs are given in Fig. 1a.

Airey *et al.* (*13*) identified the non-linear viscoelastic region of the strain sweep test data by considering the point where 5 % of the initial modulus decayed. The results of this study aligned with previous research, showing that all samples exhibited non-linear behaviour after a strain of 0.05 %. The strain values of the dough samples that passed to the nonlinear viscoelastic region were recorded as 0.05 % for the plain sample, 0.08 % for the whole egg sample, and 0.20 % for the egg yolk sample. Similarly, Mastromatteo *et al.* (*14*) prepared bread dough using durum wheat and found that the LVR was in between 0.02 and 0.065 % being consistent with the plain samples. The highest moduli were observed in the egg yolk sample. Since the dough is characterized as viscoelastic solid, the storage moduli (*G*') of each sample was greater than the loss moduli (*G*''). Within the LVR, the difference between *G*' and *G*'' was more pronounced than in the non-linear region, indicating that the elastic behaviour dominates until the structure starts to break down. As the strain amplitude increased, both moduli decreased, reflecting the disruption of the gluten-starch network. Similar behaviour was reported by Yazar *et al.* (*1*), who attributed this decrease to overstretching of the gluten network and the consequent loss of its structural integrity. Erturk *et al.* (*15*) further explained that, after the gluten network is overstretched, starch-starch interactions become more dominant, governing the viscoelastic response at large strain amplitudes. In our study, the observed reduction in *G*' and *G*'' with increasing strain can therefore be explained by the transition from a gluten-dominated to a starch dominated structural response.

In the measurement range, crossover strains (CS) were observed (see Fig. 1a). Beyond the CS value, viscous behaviour dominates, and the dough behaves liquid-like. The CS values were given in Table 1. The highest CS value was observed in Plain sample. Addition of whole egg and egg yolk prevents the gluten network formation due to lipids in the egg yolk. In the study of Alamprese *et al.* (*16*), the break load of raw pasta dough decreased as the yolk amount increased, and they explained this as the weakness of protein network due to inhibition by egg yolk lipids. The reason behind the decreasing CS with increasing egg yolk content could be the same.

The frequency sweep profile of the samples was given in Fig. 1b. In the LVR, storage modulus is greater than the loss modulus for all samples. The data obtained were fitted to the power law and the fitting results are given in Table 1.

For both *G*' and *G*'', all oscillatory flow behaviour indices (*n*) are less than 1 meaning that all the samples had shear thinning behaviour. Similarly, in the study by de la Peña *et al.* (*17*), the pasta dough prepared with various moisture contents (30–34 %) displayed shear-thinning behaviour. Both *n*' and *n*'' were highest in samples made with whole eggs, indicating that the increased oscillatory frequency results in a thicker dough compared to the other samples. For *n*', the frequency dependency decreases in the following order: whole, plain, and yolk samples. In contrast, for *n*'', the plain and yolk samples exhibit similar frequency dependencies. In the present study, the final dough moisture contents ranged approx. from 48 to 56 %, which are considerably higher than those in de la Peña *et al.* (*17*). Such higher hydration levels could be used for model pasta dough. The addition of whole egg and egg yolk leads to enhanced protein network plasticization and more pronounced viscoelastic responses. While de la Peña *et al.* (*17*) observed a decrease in apparent viscosity with increasing hydration, a similar trend can be observed in the present study since higher water content facilitates molecular mobility. This reduces the dough resistance and results in shear-thinning behaviour. The Yolk sample exhibited the highest *K*', indicating the highest stress response to oscillatory shearing. The higher *K*' value of the sample containing egg yolk may be related to the fact that the egg yolk is more viscous and has a higher solid content compared to the samples containing whole eggs and water. Even though the presence of lipids interrupts the gluten network formation and weakens the dough structure, the higher consistency coefficient at LVR could be attributed to the limited water mobility due to more viscous nature of the egg yolk. Similar trend was observed in the *K*'' values that are related to the viscous properties of the sample. Since the dough is characterized as viscoelastic solid and all samples have greater *K*' than *K*'', the increasing *K*'' values were observed as the viscosity of the liquid ingredient increased. From the perspective of dough processing, the frequency dependency of the samples is a crucial property for dough stability (*8,18*). The higher frequency dependency results in more unstable dough that could be a problem during mechanical processes. After kneading the dough, rolling and cutting steps follow and the instability such as disintegration or spring-back of the dough against these mechanical processes could interrupt the proper handling of the overall process steps.

The results of the creep-recovery test were given in Fig. 1c. J_c(t) and J_r(t) data fitted to Burger model (R^2_{adj}>0.98) are given in Table 1. It was found that 6-elements Burgers model describes both creep and recovery compliance data and it provides valuable insights for viscoelastic materials. Due to the second curvature of both creep and recovery compliance data, one more Kelvin-Voight element being serial to the 4-elements Burgers model was needed to describe the compliance behaviour. In the study of Van Bockstaele *et al.* (*19*), different cultivars of the wheat flour were used to prepare bread dough, and the creep-recovery behaviour was investigated. Similar to our findings, they discovered that the best model describing the creep behaviour was the 6-element Burgers model, while the recovery behaviour was well modelled by the 5-element Burgers model (6-elements Burgers model except for the zero-shear viscosity).

In the creep phase, 1st and 2nd elements compliances of Plain sample were found to be significantly greater than the other samples. Given the lower consistency index of the Plain sample, this difference can be attributed to its greater ability to deform under shearing. Zhang *et al.* (*20*) studied the effect of freeze-thaw cycles on the rheological properties of pasta dough and showed that the increasing number of cycles reduced the rigidity of the dough which was explained by the lowered G'. As rigidity increased, creep compliance decreased, aligning with this study's findings. The retardation times of the individual Kelvin-Voigt elements during creeping were found to consist of two distinct values, representing shorter and longer retardation times. λ_{c1}, which denotes the shorter retardation time, showed no statistically significant difference between the samples ($p<0.05$). For the longer retardation times in the creep phase, the highest value was observed in the Whole sample. The increased protein content in the Whole sample may contribute to the longer retardation time, likely due to the formation of a stronger network during kneading. The zero-shear viscosity of the Yolk sample was the highest and this value correlated with the consistency index obtained in frequency sweep test.

During recovery phase, the highest instantaneous compliance values were observed in Plain and Whole samples. As in the case of creep compliance, this phenomenon could be explained by the rigidity of the dough. For a shorter retardation time, the Plain sample exhibited the lowest value, indicating that it recovered from the deformation applied during the creep phase more quickly. The longest retardation time was observed in Yolk, followed by Plain, and then Whole samples. This could be attributed to the strength of the dough. After the rapid rearrangement of the macromolecules in the network associated with the short retardation time, the recovery of the deformation took longer in the Yolk sample, which was characterized by its stability. The zero-shear viscosity during the recovery phase was the lowest in the Plain sample.

Non-linear viscoelastic properties

Lissajous-Bowditch (L-B) curves for both elastic and viscous components of the samples were given in Fig. 2.

All samples in the L-B curves had clockwise rotation meaning that there was intracycle strain stiffening behaviour (*21*). Using L-B curves, both qualitative and quantitative measures could be obtained. For a quantitative comparison, the shape of the curves is useful. Circular structure means viscous while narrow ellipse means elastic response of the stress against the strain input (*22*). In the LVR, the stress response to the strain was linear, but after LVR the L-B curves were distorted. In the gluten and starch rich formulations, undistorted L-B curves were observed due to the reorientation of starch without gluten network disruption (*1*). As a result of this phenomenon, elasticity was provided by starch, and the intracycle linearity was observed. In the quantitative analysis of L-B curves, the area enclosed by the elastic component curve can serve as a measure of energy storage in the network against deformation. In this study, it was found that the Yolk sample had a greater enclosed area as the strain increased which means that the work done by the shearing was higher to deform that material. The trends in the increase of the enclosed areas for Plain and Whole were similar. The energy dissipation during a cycle was discussed in the studies of Duvarci *et al.* (*21*) and Ozcan *et al.* (*23*) which explained the projection area of the stress-strain curves.

Strain stiffening ratio (S) and thickening ratio (T) were presented in Fig. 3a and Fig. 3b, respectively.

The physical meaning of S value is intracycle strain softening when less than 0 and intracycle strain stiffening when greater than 0 (*10*). The Plain and Whole samples showed strain stiffening behaviour after 1 % oscillatory strain, whereas the Yolk sample exhibited this behaviour after 10 % strain. The meaning of T indicates shear thinning when T is less than 0 and shear thickening when T is greater than 0. The Plain sample had the lowest strain value where dough passes to the shear thinning behaviour. The next formulation was with Whole egg and the highest strain requirement belonged to the Yolk sample. Simultaneous classification of stiffening and thickening behaviour based on S and T were given in Fig. 3c. At small strain values, all samples behaved shear thickening and strain softening. As the strain increased all samples first passed to the strain stiffening region and then exhibited shear thinning behaviour. Erturk *et al.* (*15*) explained this phenomenon as the gluten network disruption with higher shearing. It was speculated that the lipids in the yolk sample inhibited gluten network formation. The trend may be attributed to the rigidity of the yolk dough, which might cause it to exhibit shear-thinning behaviour at higher deformation levels. This result provides an important insight into the dough machinability indicating that the samples containing egg yolk can resist deformation at a higher level compared to the other formulations.

Extensional rheology

Biaxial extensional stress vs strain data for all samples was presented in Fig. 4a.

It was found that the stress response of the biaxial compression was the highest in Yolk sample. The Young’s moduli (YM) of the samples were calculated as 6.32, 28.48, and 117.05 kPa for Plain, Whole and Yolk samples, respectively. The YM were calculated up to 0.01 strain value where the material passed to the non-linear viscoelastic region. Yu and Ngadi (*24*) investigated the mechanical properties of the noodle dough containing guar gum and varying moisture content. The results revealed that the decreasing moisture content increased the YM which was in line with the findings of this study, and the gum addition increased the YM by providing stronger interactions between water and macromolecules. The regions observed in the stress-strain curve were the linear elastic, plastic, and densification regions (*25*). The YM was calculated in the initial region, and as the material transitioned into the densification region, the stress difference between the samples increased. In the samples of this study, the highest densification was observed in the Yolk sample. Higher strain values in dough machinability can lead to increased stress, directly proportional to the degree of dough rolling. This yields a higher energy requirement during the rolling of the dough in other words the force applied to achieve targeted strain is greater. On the other hand, Plain sample had the lowest densification meaning that the strain induction during rolling did not cause any excessive collapse in the polymeric network formed during kneading (*4*).

Biaxial extensional viscosity profile was presented in Fig. 4b. The viscosity profile of the samples was fitted to Power-Law and the model parameters are given in Table 1. In terms of K_B, Plain and Whole samples behaved similarly and were less consistent than the Yolk sample. It was observed that the extensional thinning index decreased with the order of Yolk, Plain and Whole. Liao *et al.* (*26*) studied the biaxial extensional viscosity profile of the rolled noodle dough and explained the extensional thinning index as the orientation of the molecular chain of glutenin. The samples in this study also had egg proteins meaning that the orientation of the egg proteins was also attributed to thinning index. A lower thinning index means the ability to deform to a greater extent before a structural breakdown. The Whole sample had the lowest η_B (Table 1) value meaning that the extensibility of that sample without structural damage was the most favourable for rolling process.

Dough rolling process

The electric current measured during the rolling process was obtained by subtracting the current measured when no material was rolled from the total current during the entire rolling process. The current values were converted into torque data, as shown in Fig. 4c. The dough was fed into the roller section at the 4th second, and deposition was observed at the 20th second, indicating that the rolling process lasted 16 seconds. The calculated angular impulse of Plain, Whole and Yolk samples were (2.42±0.09), (4.32±0.05) and (5.26±0.09) N·m·s, respectively.

The values for the work done by the rollers in the pasta roller machine were estimated as (15.19±0.58), (27.14±0.30), and (33.02±0.59) J for Plain, Whole and Yolk samples, respectively. In the study conducted by Mohammed *et al.* (*27*), the rolling process of potato-based dough was examined, with energy consumption for the rollers reported to be between 31 and 40 J/kg of dough. These values are higher than those observed in the present study. This difference may be due to the gluten content in pasta dough, which facilitates a more efficient rolling process.

Correlation between rheological properties and the rolling process

Pearson's correlation test with a confidence level of 95 % was conducted to determine the interactions of the rheological properties and dough rolling process outputs evaluated. The correlation matrix was presented in Fig. 5.

The correlations of rheological properties with the work done (W) by the roller during the rolling process in the pasta machine were examined. The models developed for the significant correlations are presented in Table 2.

There was a strong negative correlation found for the crossover strain value, indicating that a higher crossover strain requires less work to roll the dough material. The main possibility of this could be rolling under the viscoelastic region. If the dough with higher crossover strain is rolled in LVR it means that the structure can stretch and align evenly. This means that the material may require less energy to process. On the other hand, the lower crossover strain provides rapid pass to nonlinear viscoelastic region where the structural breakdown yields with uneven orientation of the macromolecules. This may increase the work done during rolling which is consistent with the findings of this study.

K' and K'' values were positively correlated with the W. These parameters indicate the dough's consistency against oscillatory shear; higher consistency requires more energy to shape the dough between the rollers.

Creep compliance parameters yielded strong negative correlations with the W. Compliance refers to the amount of material deformation that occurs under constant applied stress. The negative correlation between W and compliance indicates that samples with higher compliance experienced greater deformation under the same stress, while the rolling process had the opposite effect. Another parameter obtained in the creep test is zero shear viscosity indicating the molecular interaction of the matrix against flow. There was a strong positive correlation between $\mu_{0,c}$ and W indicating that the higher $\mu_{0,c}$ corresponds to a lower tendency to flow, which requires more energy to flow.

In the recovery compliance parameters, 1st and 2nd Kelvin-Voight elements compliance values were negatively correlated with the W and the reason behind this phenomenon was similar to the creep compliance since the recovery mechanism of the network was in parallel with the creeping. Another similarity to the creep compliance is $\mu_{0,r}$ value that was positively correlated to W. Shorter retardation time of recovery phase was also positively correlated with W.

For the extensional rheological parameter, K_B was found to be positively correlated with W. The reason for this was the main deformation mechanism during the rolling process was attributed to the extensional properties of the samples (*4,5*). The W value was calculated from the energy requirement of the rolling process and this motion was characterized by the extensional flow.

Extensional stress was directly proportional to the K_B and W; therefore, these values were well correlated.

Microstructure of dough samples

The microstructure of the dough samples obtained from SEM analysis before cooking is presented in Fig. 6.

In the plain sample, it was seen that air bubbles are evenly distributed throughout the entire matrix. As the magnification ratio increases, smaller sized starch granules can be easily seen. Similarly, Alireza Sadeghi and Bhagya (*28*) studied pasta dough enriched with varying levels of mustard protein isolate and found similar results aligned with this study. They explained the small holes and the cracks by the insufficient formation of gluten network during kneading. They pointed out that the addition of mustard protein isolate created a matrix surrounding the starch granules. Unlike the Plain and Whole samples, it was observed that the Yolk sample exhibited a smoother texture due to the coating of the starch granules by the lipid content of the egg yolk. Herawati *et al.* (*29*) studied the impact of different egg fractions on gluten-free noodles and found that the egg yolk provided more intact structure around the starch granules which was in line with this study. Fig. 6 illustrates that all samples have air bubbles. In industrial production, this issue is mitigated by kneading the dough under vacuum conditions.

After cooking, a significant change was noticed in the size of the starch granules formed by gelatinization. In the Plain sample, the volume in the bubbles was partially occupied by the starch granules. In addition to the starch granules, the egg protein created a network between the granules as seen in the Whole sample. The changes seen after cooking were similar to those described by Rajeswari *et al.* (*30*), where the yolk sample created a smoother surface on the starch granules. In the study of Hager *et al.* (*31*), the cooking effect on the pasta was explained by matrix enhancement of protein coagulation around the starch granules resulting in stabilization of the dough which was consistent with the findings of Whole sample.

CONCLUSIONS

The frequency sweep test conducted in linear viscoelastic region characterized the viscoelasticity of the model pasta dough samples. Power-Law model constants showed that the consistency of the samples was different, and the Yolk sample was found to have the highest consistency. Creep-recovery test revealed the compliance behaviour of the dough samples that could be an important process parameter for dough rolling and shaping operations. The samples behaved differently in terms of their strain response, and this was due to the gluten network in the matrix. The large amplitude oscillatory shear tests showed that all samples behaved intracycle strain stiffening and shear thinning behaviour at larger strain values. The area enclosed in the Lissajous-Bowditch curves was the greatest in the Yolk sample because of the higher energy requirement to break down the network. Extensional rheology revealed that the samples obeyed Power-Law during extension, and the behaviour was strain thinning in the measurement range of extensional rheology test.

In the microstructure analysis of the model pasta dough, the samples were analysed before and after cooking. Holes were observed to be more frequent in the Plain and Whole samples compared to the Yolk sample, where a lipid layer formed over the surface of the starch granules. After cooking, the starch granules were swollen, and the protein network formation was observed in the samples using the egg constituents.

The dough-rolling process has demonstrated that the energy required to roll out model pasta dough is closely linked to its rheological properties. This study aims to provide insights into the behaviour of real-world pasta dough based on the data obtained from the model pasta dough. The findings indicate that the rheological properties of the dough can be adjusted by selecting different ingredients, which will optimize the pasta dough rolling process. Although this research was conducted on a model dough system meant to simulate the rolling process, these adjustments will enable more accurate process parameters for actual pasta production.

Overall, this work provides a novel and integrated rheological framework for understanding the mechanical behaviour of model pasta dough with egg components. By correlating various rheological techniques with rolling energy, this study contributes new insight into how egg constituents influence dough consistency, network integrity, and processing energy requirement. These findings are particularly relevant for designing ingredient formulations and processing strategies aimed at improving the efficiency and quality of pasta production.

ACKNOWLEDGEMENTS

The authors acknowledge the Centre for Materials Research (CMR) at IZTECH Integrated Research Centres (IZTECH IRC) for using the scanning electron microscopy.

FUNDING

This study was supported by the Scientific Research Project Unit of Izmir Institute of Technology under grant number of 2024IYTE-1-0022 titled “Real-Time Torque Measurement During Sheeting of Pasta Dough and Its Correlation with Rheological Properties”.

CONFLICT OF INTEREST

Authors state that there is no confliction of interest in this study.

AUTHORS' CONTRIBUTION

Berkay Berk conceptualized the work, investigated the study, conducted analyses, collected data and wrote the first draft. Şelale Öncü Glaue collected data, conducted analyses and revised the draft. Sevcan Ünlütürk conceptualized the work, supervised the study, developed the intellectual content, and made a critical review and edited the manuscript.

ORCID ID

B. Berk https://orcid.org/0000-0001-6479-8400
Ş. Öncü Glaue https://orcid.org/0000-0003-4757-6640
S. Ünlütürk https://orcid.org/0000-0002-0501-4714

REFERENCES

1. Yazar G, Duvarci OC, Tavman S, Kokini JL. Effect of mixing on LAOS properties of hard wheat flour dough. J Food Eng. 2016;190:195–204. https://doi.org/10.1016/j.jfoodeng.2016.06.011

2. Li W, Dobraszczyk BJ, Schofield JD. Stress relaxation behavior of wheat dough, gluten, and gluten protein fractions. Cereal Chem. 2003;80(3):333–8. https://doi.org/10.1094/CCHEM.2003.80.3.333

3. Larrosa V, Lorenzo G, Zaritzky N, Califano A. Dynamic rheological analysis of gluten-free pasta as affected by composition and cooking time. J Food Eng. 2015;160:11–8. https://doi.org/10.1016/j.jfoodeng.2015.03.019

4. Dufour M, Chaunier L, Lourdin D, Réguerre AL, Hugon F, Dugué A, *et al*. Unravelling the relationships between wheat dough extensional properties, gluten network and water distribution. Food Hydrocoll. 2024;146:109214. https://doi.org/10.1016/j.foodhyd.2023.109214

5. Yang Y ling, Guan E qi, Zhang L li, Li M meng, Bian K. Mechanical action on the development of dough and its influence on rheological properties and protein network structure. Food Res Int. 2022;158:111495. https://doi.org/10.1016/j.foodres.2022.111495

6. Bradford MM. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal Biochem. 1976;72(1):248–54. https://doi.org/10.1016/0003-2697(76)90527-3

7. Lin JH, Liu LY, Yang MH, Lee MH. Ethyl acetate/ethyl alcohol mixtures as an alternative to Folch reagent for extracting animal lipids. J Agric Food Chem. 2004;52(16):4984–6.
https://doi.org/10.1021/jf049360m

8. Berk B, Cankal YS, Köroğlu E, Yorulmaz H, Çavdaroğlu E, Ünlütürk S. The effect of starch types on extensional, linear and nonlinear rheological properties of starch cracker dough. Int J Biol Macromol. 2024;133848.
https://doi.org/10.1016/j.ijbiomac.2024.133848

9. Berk B, Glaue ŞÖ, Bayram ÖY, Ünlütürk S. Investigating the impact of sprouting on starch properties of wheat flour and non-linear rheological behavior of bread dough. Food Hydrocoll. 2025;111180.
https://doi.org/10.1016/j.foodhyd.2025.111180

10. Ewoldt RH, Hosoi AE, McKinley GH. New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear. J Rheol (N Y N Y). 2008;52(6):1427–58.
https://doi.org/10.1122/1.2970095

11. Oranchuk DJ, Diewald SN, McGrath JW, Nelson AR, Storey AG, Cronin JB. Kinetic and kinematic profile of eccentric quasi-isometric loading. Sport Biomech. 2024;23(6):758–71.
https://doi.org/10.1080/14763141.2021.1890198

12. Minitab Statistical Software, v. 21.2, Minitab Inc, State College, PA, USA; 2010. Available from: https://www.minitab.com

13. Airey GD, Rahimzadeh B, Collop AC. Viscoelastic linearity limits for bituminous materials. Mater Struct. 2003;36(10):643–7.
https://doi.org/10.1007/BF02479495

14. Mastromatteo M, Guida M, Danza A, Laverse J, Frisullo P, Lampignano V, *et al.* Rheological, microstructural and sensorial properties of durum wheat bread as affected by dough water content. Food Res Int. 2013;51(2):458–66.
https://doi.org/10.1016/j.foodres.2013.01.004

15. Erturk MY, Rogers SA, Kokini J. Comparison of Sequence of Physical Processes (SPP) and Fourier Transform Coupled with Chebyshev Polynomials (FTC) methods to Interpret Large Amplitude Oscillatory Shear (LAOS) Response of Viscoelastic Doughs and Viscous Pectin Solution. Food Hydrocoll. 2022;128:107558.
https://doi.org/10.1016/j.foodhyd.2022.107558

16. Alamprese C, Casiraghi E, Rossi M. Modeling of fresh egg pasta characteristics for egg content and albumen to yolk ratio. J Food Eng. 2009;93(3):302–7.
https://doi.org/10.1016/j.jfoodeng.2009.01.025

17. de la Peña E, Manthey FA, Patel BK, Campanella OH. Rheological properties of pasta dough during pasta extrusion: Effect of moisture and dough formulation. J Cereal Sci. 2014;60(2):346–51. https://doi.org/10.1016/j.jcs.2014.05.013

18. Iacovino S, Trivisonno MC, Messia MC, Cuomo F, Lopez F, Marconi E. Combination of empirical and fundamental rheology for the characterization of dough from wheat flours with different extraction rate. Food Hydrocoll. 2024;148:109446.
https://doi.org/10.1016/j.foodhyd.2023.109446

19. Van Bockstaele F, De Leyn I, Eeckhout M, Dewettinck K. Non-linear creep-recovery measurements as a tool for evaluating the viscoelastic properties of wheat flour dough. J Food Eng. 2011;107(1):50–9.
https://doi.org/10.1016/j.jfoodeng.2011.06.001

20. Zhang S, Niu M, Dang W, Han J, Liu M, Liang Y, et al. Insights into the mechanisms underlying the quality deterioration of a novel frozen pasta product during freeze–thawed cycles. Int J Food Sci Technol. 2024;59(9):6360–73.
https://doi.org/10.1111/ijfs.17377

21. Duvarci OC, Yazar G, Kokini JL. The comparison of LAOS behavior of structured food materials (suspensions, emulsions and elastic networks). Trends Food Sci Technol. 2017;60:2–11. https://doi.org/10.1016/j.tifs.2016.08.014

22. Ewoldt RH, Hosoi AE, McKinley GH. Rheological fingerprinting of complex fluids using large amplitude oscillatory shear (LAOS) flow. Annu Trans Rheol Soc. 2007;15:3.

23. Ozcan I, Ozyigit E, Erkoc S, Tavman S, Kumcuoglu S. Investigating the physical and quality characteristics and rheology of mayonnaise containing aquafaba as an egg substitute. J Food Eng. 2023;344:111388.
https://doi.org/10.1016/j.jfoodeng.2022.111388

24. Yu LJ, Ngadi MO. Rheological properties of instant fried noodle dough as affected by some ingredients. J Sci Food Agric. 2006;86(4):544–8.
https://doi.org/10.1002/jsfa.2381

25. Sadighi M, Salami S. An investigation on low-velocity impact response of elastomeric & crushable foams. Open Eng. 2012;2(4):627–37.
https://doi.org/10.2478/s13531-012-0026-0

26. Liao HJ, Chung YC, Tattiyakul J. Biaxial extensional viscosity of sheeted noodle dough. Cereal Chem. 2007;84(5):506–11.
https://doi.org/10.1094/CCHEM-84-5-0506

27. Mohammed MAP, Tarleton E, Charalambides MN, Williams JG. Mechanical characterization and micromechanical modeling of bread dough. J Rheol (N Y N Y). 2013;57(1):249–72. https://doi.org/10.1122/1.4768463

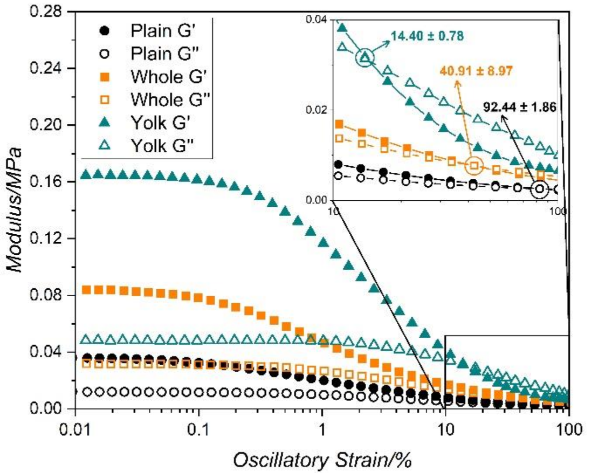
28. Alireza Sadeghi M, Bhagya S. Quality characterization of pasta enriched with mustard protein isolate. J Food Sci. 2008;73(5):S229–37. https://doi.org/10.1111/j.1750-3841.2008.00742.x

29. Herawati H, Kamsiati E, Sunarmani. Formulation of food Ingredients (peanut flour, egg yolks, egg whites, and guar gum) to the characteristics of gluten-free noodles. Int J Technol. 2021;12(3):602–12. https://doi.org/10.14716/ijtech.v12i3.4139

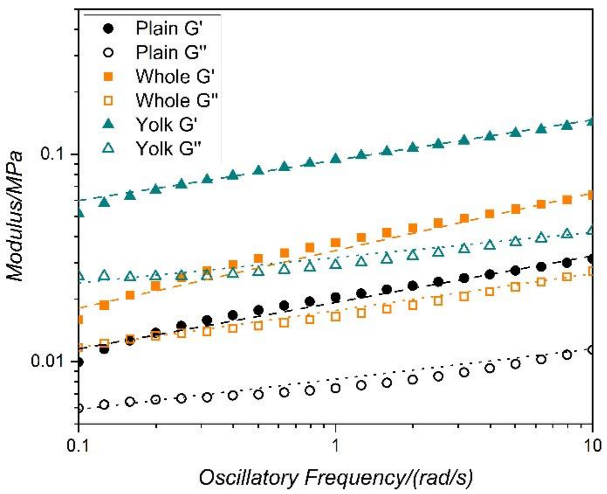
30. Rajeswari G, Susanna S, Prabhasankar P, Venkateswara Rao G. Influence of onion powder and its hydrocolloid blends on pasta dough, pasting, microstructure, cooking and sensory characteristics. Food Biosci. 2013;4:13–20. https://doi.org/10.1016/j.fbio.2013.07.004

31. Hager AS, Lauck F, Zannini E, Arendt EK. Development of gluten-free fresh egg pasta based on oat and teff flour. Eur Food Res Technol. 2012;235(5):861–71. https://doi.org/10.1007/s00217-012-1813-9

a)


Plain G'
Plain G''
Whole G'
Whole G''
Yolk G'
Yolk G''
14.40 ± 0.78
40.91 ± 8.97
92.44 ± 1.86
Modulus/MPa
Oscillatory Strain/%

b)


Plain G'
Plain G''
Whole G'
Whole G''
Yolk G'
Yolk G''
Modulus/MPa
Oscillatory Frequency/(rad/s)

c)

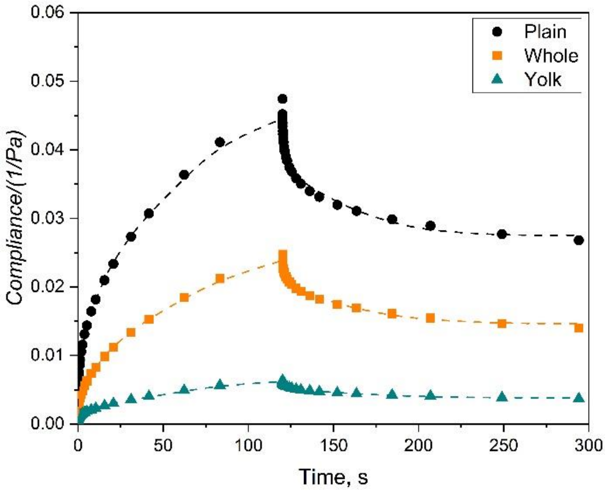
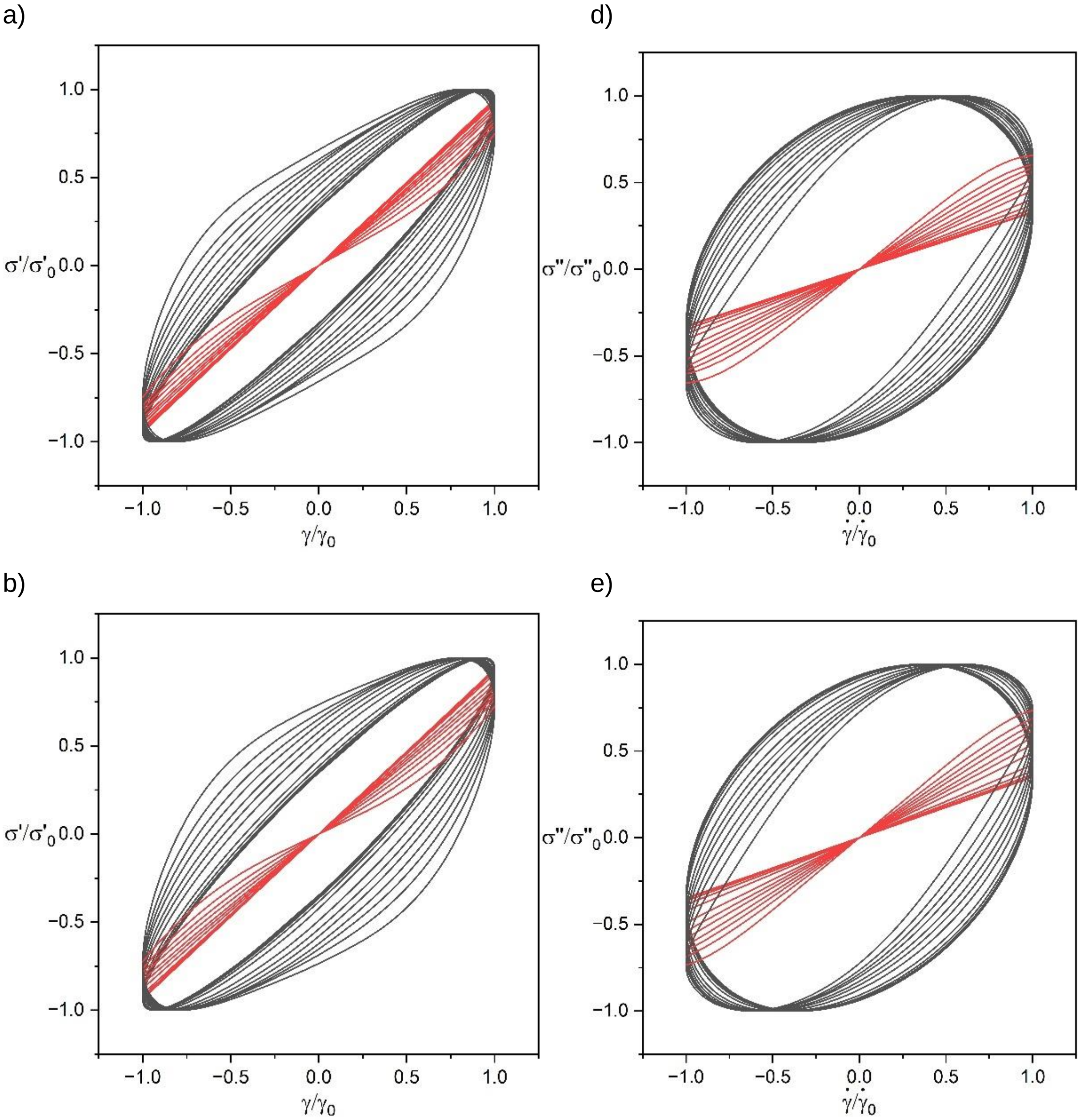
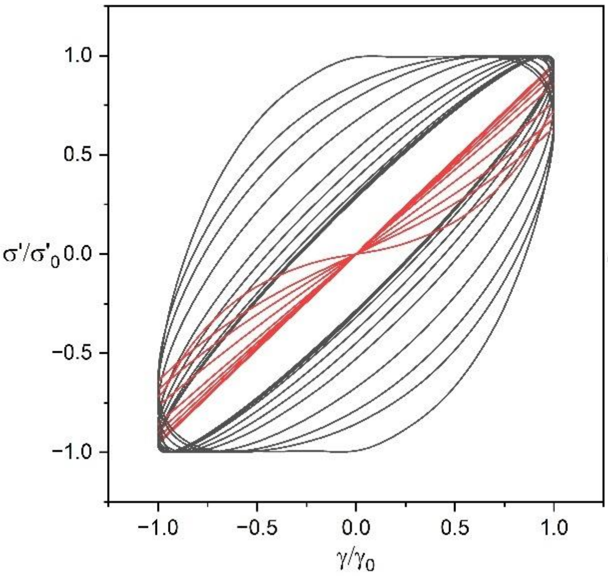

Plain
Whole
Yolk
Compliance/(1/Pa)
Time, s

Fig. 1. a) strain sweep (with CS values marked), b) frequency sweep and c) creep-recovery profiles of the dough samples prepared with only water (plain, circles), whole egg (squares), and egg yolk (triangles)



c)



f)

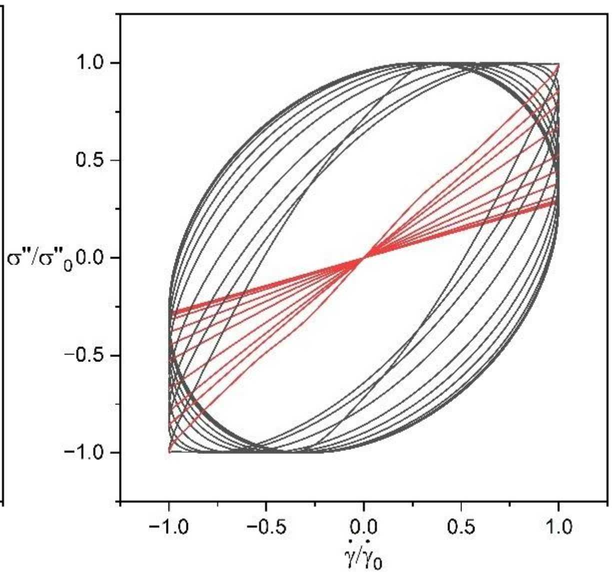
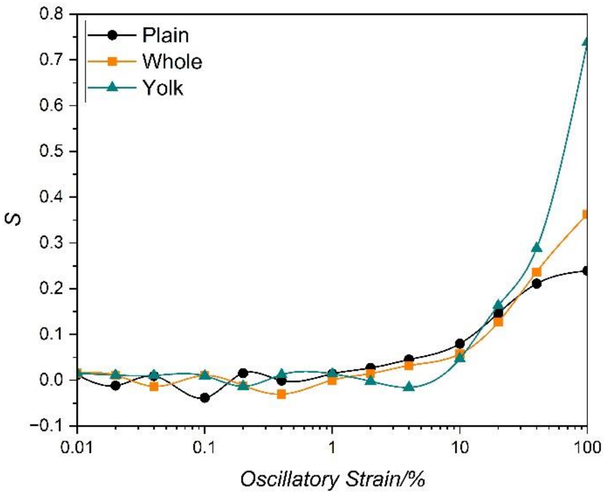
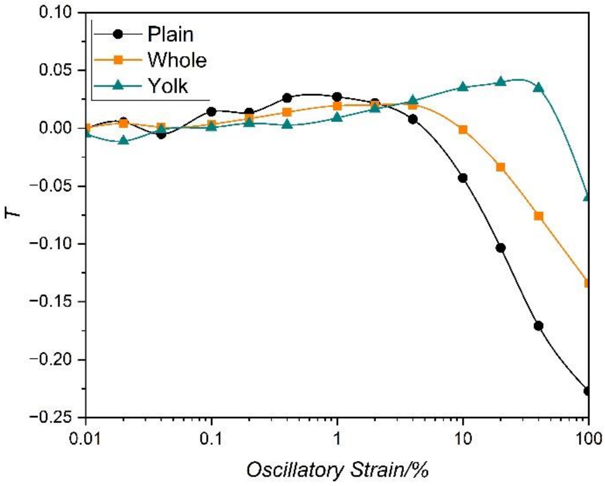


Fig. 2. Lissajous-Bowditch curves of elastic components of a) Plain, b) Whole, c) Yolk and viscous components of d) Plain, e) Whole, f) Yolk samples.

a)



b)



c)

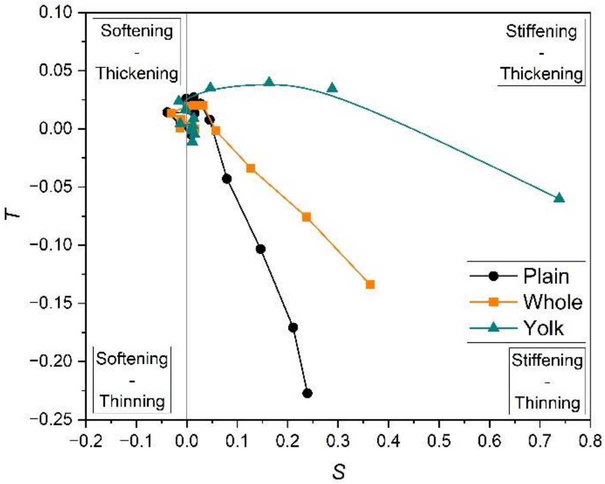
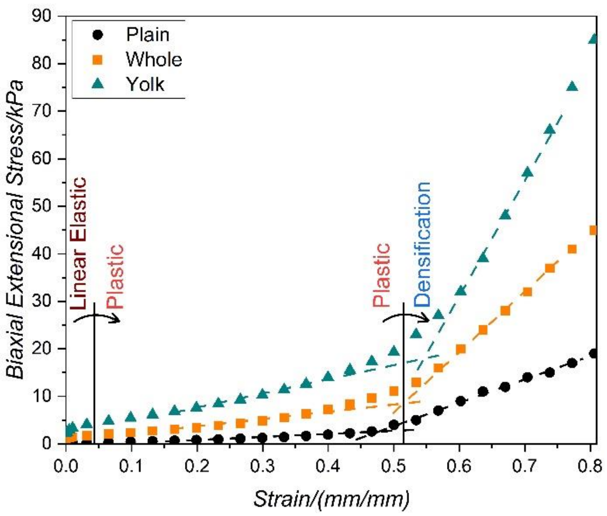
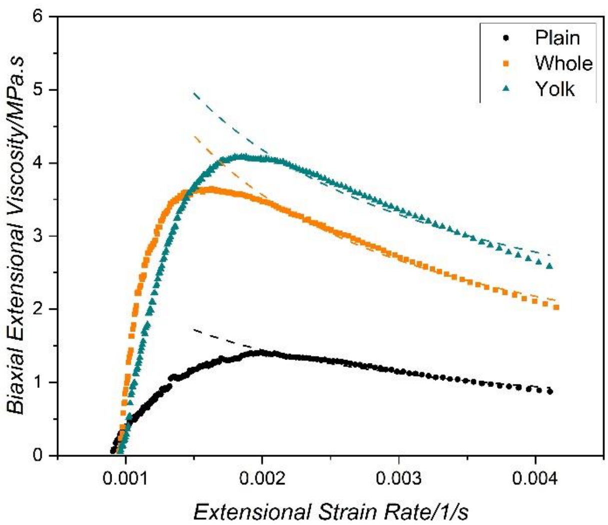


Fig. 3. a) strain stiffening and b) thickening ratio with respect to oscillatory strain amplitude. c) S vs T values

a)


Plain
Whole
Yolk
Linear Elastic
Plastic
Plastic
Densification
Biaxial Extensional Stress/kPa
Strain/(mm/mm)
0
10
20
30
40
50
60
70
80
90
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

b)


Plain
Whole
Yolk
Biaxial Extensional Viscosity/MPa.s
Extensional Strain Rate/1/s
0
1
2
3
4
5
6
0.001
0.002
0.003
0.004

c)

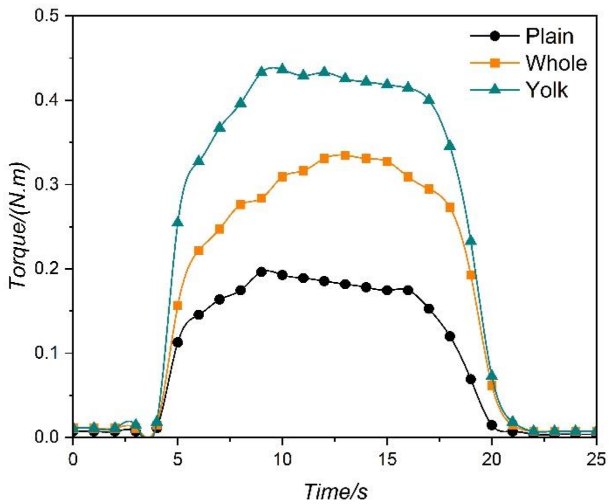


Fig. 4. a) biaxial extensional stress vs strain, b) biaxial extensional viscosity profile and c) torque change during rolling.

	CS	K'	n'	K''	n''	J_{c0}	J_{c1}	J_{c2}	λ_{c1}	λ_{c2}	μ_{0c}	J_{r0}	J_{r1}	J_{r2}	λ_{r1}	λ_{r2}	μ_{0r}	K_B	n_B
K'	-0.86																		
n'	0.11	-0.57																	
K''	-0.93	0.98	-0.39																
n''	0.00	-0.50	0.97	-0.33															
J_{c0}	0.95	-0.93	0.24	-0.98	0.19														
J_{c1}	1.00	-0.85	0.08	-0.93	-0.01	0.96													
J_{c2}	0.96	-0.94	0.29	-0.97	0.20	0.97	0.95												
λ_{c1}	0.31	-0.64	0.86	-0.50	0.76	0.35	0.25	0.50											
λ_{c2}	0.48	-0.83	0.92	-0.70	0.86	0.59	0.46	0.63	0.85										
μ_{0c}	-0.87	0.98	-0.59	0.95	-0.49	-0.91	-0.85	-0.93	-0.66	-0.86									
J_{r0}	0.57	-0.84	0.87	-0.72	0.75	0.60	0.53	0.67	0.88	0.96	-0.88								
J_{r1}	0.97	-0.92	0.20	-0.98	0.15	1.00	0.98	0.96	0.31	0.57	-0.90	0.59							
J_{r2}	0.98	-0.78	-0.06	-0.88	-0.14	0.94	0.99	0.91	0.12	0.33	-0.77	0.39	0.96						
λ_{r1}	-0.91	0.65	0.25	0.79	0.29	-0.88	-0.93	-0.83	0.07	-0.16	0.63	-0.19	-0.90	-0.98					
λ_{r2}	-0.18	0.63	-0.99	0.47	-0.97	-0.33	-0.16	-0.35	-0.81	-0.95	0.65	-0.87	-0.30	-0.03	-0.14				
μ_{0r}	-0.83	0.52	0.39	0.68	0.42	-0.80	-0.85	-0.75	0.17	0.00	0.50	-0.03	-0.81	-0.92	0.98	-0.30			
K_B	-0.85	0.98	-0.59	0.95	-0.49	-0.88	-0.82	-0.93	-0.74	-0.83	0.97	-0.88	-0.86	-0.74	0.59	0.63	0.46		
n_B	-0.12	0.58	-0.99	0.41	-0.98	-0.28	-0.10	-0.32	-0.85	-0.93	0.60	-0.85	-0.23	0.04	-0.20	0.99	-0.34	0.59	
W	-0.99	0.87	-0.10	0.94	-0.02	-0.98	-1.00	-0.96	-0.26	-0.48	0.86	-0.53	-0.99	-0.99	0.93	0.19	0.86	0.83	0.13

Fig. 5. Pearson's correlation matrix of the parameters. Numbers in the colour boxes represent the corresponding correlation coefficient. Colour scale is set as red is positive correlation and blue is negative correlation

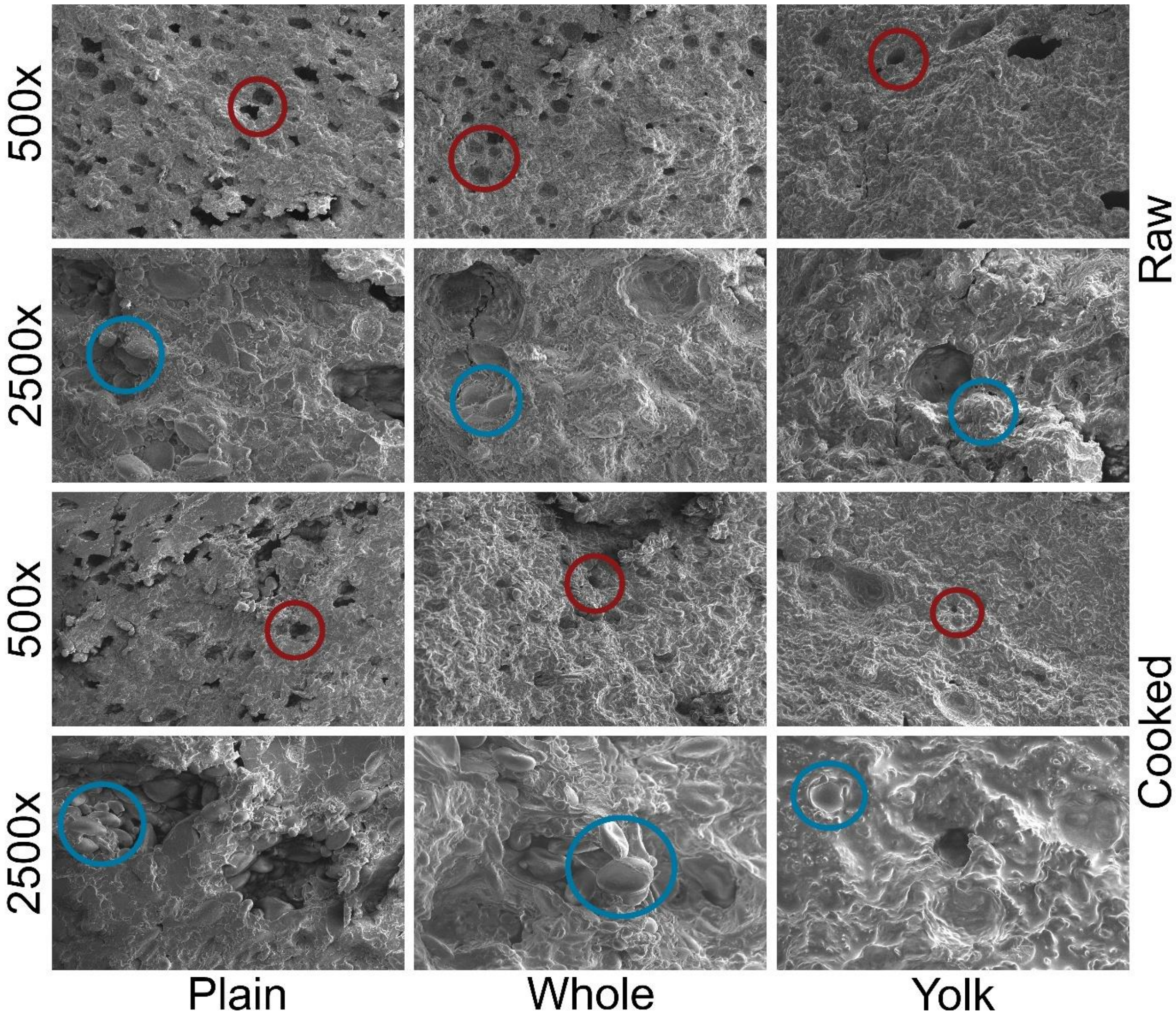


Fig. 6. Microstructure of the dough samples before and after cooking. Red circles indicate air bubbles and blue circles indicate starch granules

Table 1. Crossover strain values and the rheological model fitting parameters

Test	Parameter	Plain	Whole	Yolk
Strain sweep	CS/%	(92.44±1.86)^{A}	(40.91±8.97)^{B}	(14.40±0.78)^{C}
Frequency sweep	K'/(MPa·s$^{n'}$)	(0.020±0.001)^{B} R^2=0.98	(0.036±0.006)^{B} R^2=0.99	(0.092±0.006)^{A} R^2=0.99
	n'	(0.226±0.003)^{B} R^2=0.98	(0.277±0.001)^{A} R^2=0.99	(0.204±0.002)^{C} R^2=0.99
	K''/(MPa·s$^{n''}$)	(0.008±0.000)^{C} R^2=0.96	(0.017±0.003)^{B} R^2=0.98	(0.031±0.002)^{A} R^2=0.94
	n''	(0.130±0.001)^{B} R^2=0.96	(0.177±0.016)^{A} R^2=0.98	(0.116±0.002)^{B} R^2=0.94
Creep compliance	J_{c0}/(1/Pa)	(0.0026±0.0001)^{A} R^2=0.99	(0.0014±0.0004)^{B} R^2=0.99	(0.0004±0.0001)^{C} R^2=0.99
	J_{c1}/(1/Pa)	(0.0061±0.0004)^{A} R^2=0.99	(0.0023±0.0002)^{B} R^2=0.99	(0.0006±0.0001)^{C} R^2=0.99
	J_{c2}/(1/Pa)	(0.0121±0.0016)^{A} R^2=0.99	(0.0069±0.0003)^{B} R^2=0.99	(0.0016±0.0004)^{C} R^2=0.99
	λ_{c1}/s	(0.3199±0.1078)^{A} R^2=0.99	(0.4785±0.0968)^{A} R^2=0.99	(0.1658±0.0639)^{A} R^2=0.99
	λ_{c2}/s	(13.036±0.1231)^{B} R^2=0.99	(16.075±0.2210)^{A} R^2=0.99	(7.4150±0.6760)^{C} R^2=0.99
	μ_{c0}/(Pa·s)	(4069±393)^{B} R^2=0.99	(8518±804)^{B} R^2=0.99	(26355±1678)^{A} R^2=0.99
Recovery compliance	J_{r0}/(1/Pa)	(0.0086±0.0007)^{A} R^2=0.98	(0.0114±0.0023)^{A} R^2=0.99	(0.0014±0.0002)^{B} R^2=0.98
	J_{r1}/(1/Pa)	(0.0072±0.0003)^{A} R^2=0.98	(0.0036±0.0008)^{B} R^2=0.99	(0.0009±0.0001)^{C} R^2=0.98
	J_{r2}/(1/Pa)	(0.0305±0.0013)^{A} R^2=0.98	(0.0082±0.0004)^{B} R^2=0.99	(0.0035±0.0008)^{C} R^2=0.98
	λ_{r1}/s	(0.0099±0.0042)^{B}	(1.0930±0.1460)^{A}	(1.0662±0.0938)^{A}

		R^2=0.98	R^2=0.99	R^2=0.98
	λ_{r2}/s	(97.490±6.840)[B] R^2=0.98	(47.740±9.070)[C] R^2=0.99	(127.40±3.980)[A] R^2=0.98
	μ_{r0}/(Pa·s)	(23436±16662)[B] R^2=0.98	(141327±14655)[A] R^2=0.99	(119029±12203)[A] R^2=0.98
Extensional rheology	K_B/(MPa·s^{nB})	(0.0351±0.0039)[B] R^2=0.96	(0.0472±0.0060)[B] R^2=0.99	(0.1005±0.0112)[A] R^2=0.97
	n_B	(0.389±0.007)[B] R^2=0.96	(0.289±0.013)[C] R^2=0.99	(0.412±0.009)[A] R^2=0.97

*Mean within a row followed by different letters (A-C) is significantly different. R^2 represents the adjusted R^2 of the model fitted.

Table 2. Models developed for the correlation analysis with the work done

Correlated parameter	Model	R^2
CS	CS=-4.3509W+158.5	0.98
K'	CS=0.0037W+0.0427	0.76
K''	CS=0.0012W-0.00116	0.89
J_{c0}	CS=-0.0001W+0.0044	0.96
J_{c1}	CS=-0.0003W+0.0107	0.99
J_{c2}	CS=-0.0006W+0.0209	0.92
μ_{0c}	CS=1120.9W-15167	0.74
J_{r1}	CS=-0.0003W+0.0126	0.98
J_{r2}	CS=-0.0016W+0.0533	0.97
λ_{r1}	CS=0.0639W-0.8827	0.87
μ_{0r}	CS=6009.6W-56311	0.73
K_B	CS=0.0032W-0.0203	0.70

*R^2 represents the adjusted R^2 of the model fitted