

14 The Role of Gluten Elasticity in the Baking Quality of Wheat

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14.1 Introduction

Articles dealing with elasticity usually start by describing it as the most important unique property of wheat. Elasticity is believed to account for the high specific volume of bread and its high and rounded loaf shape when baked without the support of a pan.

It is generally assumed that the simultaneous presence of elastic proteins and special bread quality proves that elastic proteins are sufficient to explain the good bread volume. However, what if it is just a coincidence?

Besides proteins and their elastic properties, numerous other flour ingredients with functional properties are present in wheat which might be the real source of the baking potential. So there is a need to analyse the function of elasticity more closely.

14.2 Definition of Baking Quality

The definitions of bread quality vary from country to country and from person to person. Sometimes a high specific volume or an elastic crumb are not accepted as a sign of good quality. However, the volume measured at a defined

form ratio (height/width) is an international criterion for quality on the wheat market.

The volume can be determined by standardized baking tests according to the AACC or the ICC, or on a micro-scale with 7 to 10 g of flour (Kieffer *et al.*, 1993 and 1998). This is how the dependent variable for the analysis of the correlation between bread quality and elasticity is defined.

14.3 Definition of Elasticity

Elasticity is closely related to vulcanized rubber. But the fully cross-linked structure of rubber cannot be used to explain gluten elasticity. Both are of high molecular weight, but gluten is a non-cross-linked material. The molecules can be separated at least partially by dissociating agents like sodium dodecylsulfate (SDS).

"Elasticity" in bakery is a sensory perception that is felt when the dough is rapidly stretched and released. Elasticity is good when the dough contracts rapidly to approximately its original shape. In another test the baker tries to stretch the dough into a thin membrane (Fig. 82). The formation of membranes with no fissures is attributed to good gluten quality

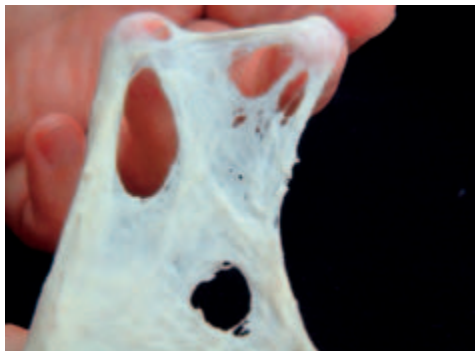


Fig. 82: Stretching of a piece of dough (left) and of gluten (right) in two dimensions, creating fissures

and therefore an indication of good elasticity. During kneading, dough will wind up the hook when the kneading optimum approaches (Fig. 83). This so-called Weissenberg effect is a sign of elasticity too.

These observations are mainly of a qualitative nature and lead us to expect a good product. A scale for elastic behaviour can be derived from Hook's law.

The deformation of an ideal elastic solid is totally recoverable. This deformation is described by the equation:

$$D = \frac{F}{G} \text{ (Hook's law)}$$

- D = Elastic deformation
- F = Force
- G = Modulus

An elastic solid will be the more extensible at a given force the lower the modulus G is. So to determine G could objectify the sensory tests.

14.4 Elasticity of Gluten and Dough

For most real solid materials elasticity is one of three physical parameters contributing to firmness. The materials exhibit elasticity, viscosity and cohesiveness simultaneously, which makes it difficult to measure elasticity independently of viscosity and cohesiveness. Gluten and dough are normally said to be viscoelastic. Both exhibit solid-like properties

(cohesiveness and elasticity) and liquid-like properties (viscous or unrecoverable deformability).

Hook's law is not, therefore, applicable to dough or gluten. Elasticity has to be determined from the resulting rheological property. There are in fact methods for separating elastic and viscous behaviour, but a comparison of different samples is only permissible if cohesiveness is comparable. However, cohesiveness cannot be determined since there is no method for doing so with samples like dough.

14.5 The Role of Molecular Weight in Elasticity

In addition to rheological tests to quantify elasticity, chemical modifications of gluten proteins have been used to demonstrate the importance of elasticity for baking.

These methods alter elastic behaviour by changing the molecular weight of glutenin or its solubility:

The partial or total reduction of intermolecular disulphide bonds lowers both molecular weight and elasticity (Belitz *et al.*, 1986) and is detrimental to baking. High-pressure treatment (Kieffer and Wieser, 2004) or enzymes like transglutaminase (Bauer *et al.*, 2003) create new covalent bonds and raise the molecular weight of gluten. This can lead to less viscous and more elastic gluten and higher dough stability.



Fig. 83: Sensory testing of dough and the Weissenberg effect resulting from elasticity

14.6 The Role of Non-Covalent Interactions

But the high molecular weight of glutenin is not the only reason for the occurrence of elasticity. It is the fact that gluten proteins are exceptionally cohesive, mainly because of their ability to form hydrogen bonds between the amide side chains of the amino acid glutamine, which accounts for about 35% of all residues (Fig. 84).

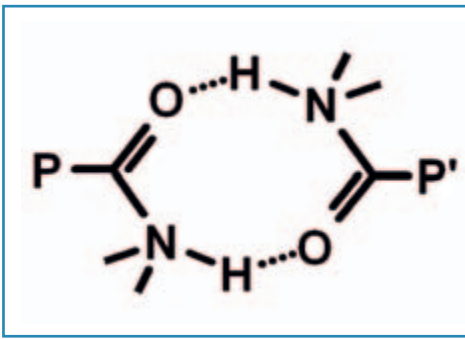


Fig. 84: Two amide groups of glutamine of adjacent gluten chains (P and P') linked by two hydrogen bonds (dotted) sharing hydrogen atoms

Hydrogen bonds interchange easily, which means that unlike the covalent disulphide bonds they can be separated and fixed again during deformation of the material. Nevertheless, their total binding energy in

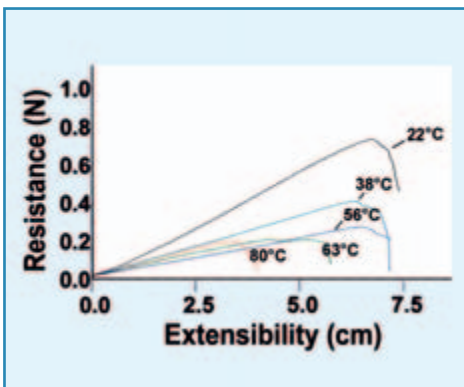


Fig. 85: Resistance and extensibility of gluten at various temperatures (micro-Extensograph)

gluten may be considerable: 10 hydrogen bonds equal the strength of one disulfide bond, and over 30 times more hydrogen bonds can be formed than disulfide bonds because of the great number of glutamine residues in gluten. The function of these bonds can be observed when dough is cooled or heated. At low temperatures hydrogen bonds are strengthened, whereas at high temperatures the opposite is the case. The firmness and elasticity of gluten (Fig. 85) and dough are changed in the same manner. Up to 60 °C resistance decreases, then heat denaturing begins and extensibility decreases too.

14.7 The Role of the Insolubility of Gluten

Cohesiveness is lost as the proteins become more soluble. Their native insolubility is due to a small and well-balanced amount of anionic and cationic amino acid side chains and of the end-groups of the subunits (Belitz *et al.*, 1982). Changing the number of one sort of ion e.g. by derivatisation of amino groups to carboxylic groups (Dirndorfer *et al.*, 1986) solubilizes gluten without changing the molecular weights, with the result that elasticity is lost completely.

When experiments in which the solubility of gluten is changed are used to deduce the importance of elasticity for wheat bread making, it must be kept in mind that in fact the composition of the dough is changed. In the case of reduced disulfide bonds, or when gluten fractions are made water-soluble, the nature of the gluten is changed completely, in other words there is no longer any gluten in the dough capable of generating cohesive structures. It is like cutting a rubber band in small pieces. The elastic behaviour vanishes because of a lack of cohesiveness of the pieces. There is still rubber, but no longer a rubber band.

A better way to prove the correlation between elasticity and baking quality is to compare flours from different wheat cultivars by the following rheological methods.

14.8 Methods for the Evaluation of Elasticity

14.8.1 Prerequisites for Physical Testing

Elasticity is only one component of the bulk property of gluten or dough, so methods must be used which show this property isolated from the others.

A second problem is that when gluten and dough are compared it is essential for both samples to have exactly the same dimensions. It is rather difficult to shape gluten. But this can be done by using parallel plate geometries with stress rheometers or the SMS/Kieffer gluten and dough extensibility method (Kieffer *et al.*, 1998 and Mann *et al.*, 2004) or high-pressure capillary viscosimetry (Kieffer *et al.*, 1982). The latter will not be considered as it is very time-consuming.

The third and most important question is what we want to see. Cereal chemists want to clarify the mechanism of elasticity on a molecular basis, and determinations in the field of linear viscoelasticity can be useful. If, on the other hand, the function of elasticity during dough preparation and for the resulting product is of interest, we first have to find the range of stress or deformation velocity; that means we have to imitate very closely what happens in dough. Because this is not so simple we have to vary test conditions until they are correlated e.g. to the baked volume. Using this approach, very useful empirical methods such as the Brabender methods have been developed.

14.8.2 Instruments and Parameters

In so-called dynamic measurements with parallel-plate rheometers the material is subjected to very small oscillating movements – in

our experiments (Tab. 67) less than 3 μm – so the properties are determined under conditions where the structure of dough and gluten is presumably not destroyed. The elastic and viscous resistance at a given deformation can be calculated. The relative contributions of the viscous and elastic components to the rheological properties of the sample are expressed by $\tan \delta$ (see chapter 13.1.5, page 138).

$$\tan \delta = \frac{G''}{G'}$$

in which G'' is called the loss modulus, a measure of viscosity, and G' the storage modulus, a measure of elasticity. Both are derived from δ and from the complex shear modulus G^* which represents the total resistance of dough or gluten to imposed deformation.

Larger deformations between 3 and 9 mm can be used with creep and creep-relaxation tests. Here the sample is loaded with a sudden stress that is kept constant for a certain time. Then the stress is removed and the sample is allowed to relax. This test gives information on the total deformation Δ (%) or the ease of deformation under constant stress, and also the magnitude of the elastic deformation (E) and the irreversible, viscous deformation (V). A third easy rheological test is the micro-extension test (Kieffer, 1981). It is similar to the Brabender test, but uses samples of constant diameter and a Texture Analyser (see chapter 13.1.4, page 135). In this way, gluten and dough properties can be compared by the same method. This test is a rupture test showing the behaviour of the material at large and rapid deformations. Elastic properties can tentatively be evaluated from the initial slope of the Extensograms. The force at the breaking point of the dough, the maximum resistance (Re) and the extensibility (Ex) are recorded.

Dough and gluten properties monitored by dynamic (oscillatory) methods

G'	=	storage modulus, signifies the contribution of elasticity to the rheological properties
G''	=	loss modulus, the contribution of viscosity to the rheological properties
G^*	=	complex shear modulus G^* , represents the total resistance of dough to imposed deformation
$\tan \delta$	=	tangent delta, ratio of viscous and elastic behaviour (G''/G')

14.9 Comparative Tests with Various Rheological Methods to Reveal the Function of Elasticity

It is a well established fact that rheological properties largely govern dough development and baking (see chapter 13.1.4). Tests made at different shear velocities show that the elasticity of the dough is linked to the elasticity of the gluten and that elasticity can influence the baked volume.

14.9.1 Materials

Seven wheat cultivars differing in protein content (N = 1.44 - 2.04%) and protein quality (gliadin / glutenin ratio = 1.72 - 2.61) from the quality classes E (extra high) to C (not bread quality) were analysed by the methods described above. Rounded and non-rounded doughs were used. Both have the same composition but the mechanical input is different. Non-rounded dough is shaped into

test pieces within 20 s after kneading in a Farinograph, rounded dough is left to relax for 10 min then rounded as in a baking test. These two types of dough were compared because non-rounded doughs are normally used in dough testing, but rounded dough is used for most bread-making processes. Rounding after a short relaxation time changes the gluten and starch structures as shown in Fig. 86.

This makes the form ratio of bread better at a comparable fermentation time. This gentle action is said to cause hardening of the gluten structures, but in fact more cohesive and thicker structures are built up (Kieffer and Stein, 1999). The small and feeble gluten filaments separate from starch and starch kernels are packed more closely. This also helps to stabilize the dough.

14.9.2 Results

Tab. 67 shows the best coefficients of correlation between the different rheological parameters monitored for gluten, rounded and non-rounded dough and baking volume.

Tab. 67: Highest correlation coefficients (r) obtained by comparison between baking results and rheological properties measured on gluten and dough in dynamic, creep and creep recovery tests and with micro-Extensograms; n = 7; 95.0% confidence level at r > 0.727 (correlated); 99.0% at r > 0.837 (high correlation); 99.9% at r > 0.924 (very high correlation)

Correlation between		Compared properties		r
Object A	Object B	Object A	Object B	
Gluten	Gluten	Re	Δ	-0.800
		Re	V	-0.920
		Re	E	-0.920
Gluten	Non-rounded dough	E	E	0.496
		G'	G'	0.397
Gluten	Rounded dough	V	V	0.731
		E	E	0.922
		G''	G''	0.474
		G'	G'	0.397
Non-rounded dough	Rounded dough	Re	Re	0.990
Gluten	Bread	G*	Vol	-0.826
Non-rounded dough	Bread	Re	Vol	0.913
Rounded dough	Bread	Re	Vol	0.927
		G*	Vol	-0.850

Δ = total deformation; Re = resistance; Ex = extensibility; E = elastic deformation; V = viscous deformation; Vol = volume yield; G' = storage modulus; G'' = loss modulus; G* = complex shear modulus

A very good correlation of $r=0.922$ was found between gluten and rounded dough or the elastic deformation E but not between gluten or dough and baked volume. Neither the dynamic moduli G' and G'' nor $\tan \delta$ were useful in comparing gluten and dough properties or predicting baked volume. The sole value of G^* for gluten and dough was highly but negatively correlated to the volume. G^* is a measure of the resistance of the material to deformation. That means that when the gluten or dough is too strong, the volume will be low, a fact well known in practice.

The very high coefficient between E of gluten and E of rounded dough shows that in this case the gluten properties are more apparent than in non-rounded dough. As we said above, this results from better aggregation of gluten through rounding and the formation of a more continuous network.

14.9.3 Correlations between Rheological Properties and Baked Volume Show that Cohesiveness is the Key

From the high negative correlation of G^* , the high positive correlation of Re and the non-existent correlation of any elastic modulus or deformation to volume, the conclusion can be drawn that elasticity is not involved in volume generation. The rupture tests mainly monitor the cohesiveness of dough. The better this is, the greater will be the expansion of dough during proofing and oven rise.

14.10 The Mechanism of Elastic Deformation

14.10.1 The Role of Gliadin and Glutenin

Although elasticity does not play the major role we expected, it is interesting to look at the origins of elasticity. Chemical properties and

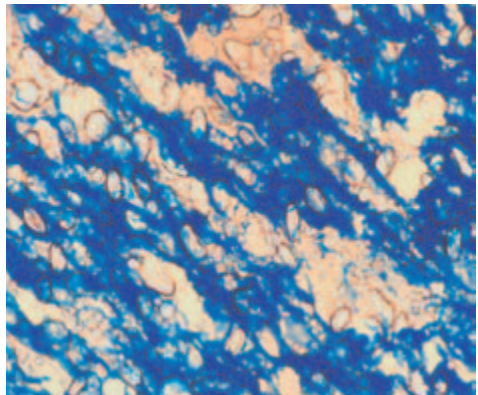
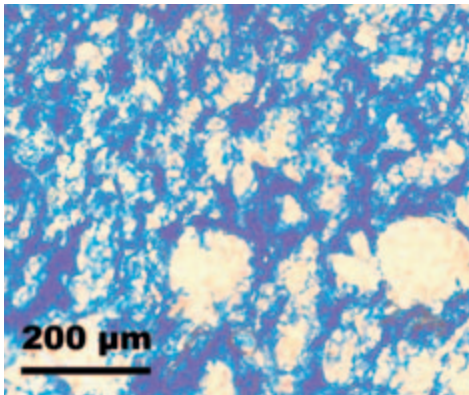


Fig. 86: Sections of dough (40 μm); proteins stained blue. Dough not rounded (left) and rounded (right) with the corresponding micro-baking results (bottom).

aggregates with high molecular weight will be of importance. But cereal chemists are far from having a full explanation.

Gluten proteins can be divided into two fractions according to their solubility: the gliadins account for 65 to 75% of the gluten and the glutenins for the rest. Gliadins are mainly monomer with molecular weights ranging from 30,000 to 50,000 and soluble in 50% ethanol. Glutenins are polymeric with molecular weights from 400,000 to more than 1 million, presumably up to 10 million. They are insoluble in ethanol. So far it has not been possible to determine the real molecular weight because of big, insoluble particles sometimes called glutenin macro polymers (GMP), which cannot be dissolved or separated but are necessary for molecular weight determination.

In an aqueous milieu gliadin is a honey-like viscous fluid, whereas pure glutenin is hardly extensible, very strong and mainly elastic as can be seen from Tab. 68.

The proper mixture of gliadin and glutenin is responsible for the viscoelastic properties and ease of extensibility under the low pressure generated by yeast. That is why gliadin is sometimes regarded as a plasticizer or solvent for glutenin. But this would only be true if the two fractions were homogeneously mixed. This is not the case, as I will show by following the hydration process of the proteins and their mechanism of elongation and rupture.

Besides the quality of protein fractions their quantity is an important factor for functionality and for the resulting dough properties and baking results (Wieser and Kieffer, 2001). To a large extent it is the gliadin / glutenin ratio

Tab. 68: Rheological properties of gliadin, glutenin and whole gluten. Results of dynamic testing at 1 Hz and 0.15% deformation and as shown in micro-Extensograms.

Substance	Dynamic test			Extensograms	
	G Pa	G Pa	tan δ	Re N	Ex cm
Gliadin	561	657	1.2	n.m.	n.m.
Glutenin	38580	8986	0.2	4.7	2.2
Gluten	2506	1321	0.5	1.34	8.4

n.m. = not measurable

that determines the firmness and elasticity of gluten (Fig. 87; Kim *et al.*, 1988). The amount of glutenin and GMP particles in flour increases dough firmness and kneading time (Weegels *et al.*, 1996).

14.10.1 What Makes Glutenin Elastic?

Is it the primary structure of the subunits, the concatenation by intermolecular disulfide bonds, the shape of the polymeric proteins?

The primary structure of the subunits is formed by a large repetitive domain containing mainly the amino acids glutamine, proline and glycine. The sequence of these amino acids is able to adopt a regular spiral configuration (Shewry *et al.*, 1998), which resembles a metal spring. It has therefore been admitted that these domains might be rod-like and have elastic properties. Numerous springs linked together by the covalent disulphide bonds might form an elastic filament. But molecules of this shape are only conceivable at high shear forces. Relaxed gliadin, glutenin subunits and glutenin polymers soluble in acetic acid were made visible by transmission electron microscopy at a magnification of 10,000x. At low concentrations filament-shaped particles were not detected – only globular forms as can be seen in Fig. 88.

Because of the large number of possible intra-

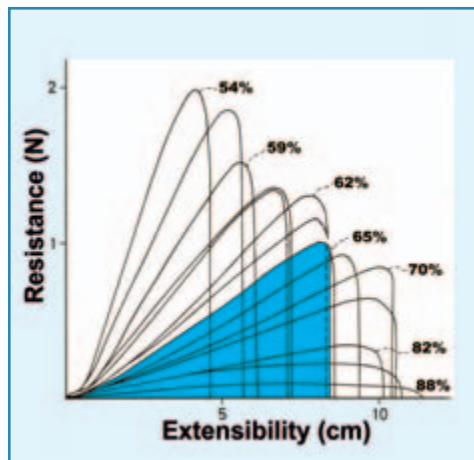


Fig. 87: Micro-Extensograms of gluten with different gliadin levels (% of total gluten)

moleculare interactions, e.g. by hydrogen bonds, the energetically most stable shape of monomeric and polymeric single gluten molecules in water is a rather round one.

The filament structure of the polymers also has to be revised since the positions of the sulfhydryl groups, which are able to form intermolecular bonds, have been localized (Köhler *et al.*, 1993). It is now clear that the polymers are highly branched. There are three different types of glutenin subunits characterised by two or more sulfhydryl groups able to form interchain bonds (Fig. 89). The subunits with a high molecular weight (HMW) have more than two cysteine residues and appear to form the backbone of the polymers to which branches of low molecular weight subunits (LMW) are attached. These have two cysteine residues capable of forming linear polymers only. The most probable structure of a basic molecular unit of glutenin polymers is shown by the model by Wieser (Wieser *et al.*, 2005) (Fig. 89) which already has a molecular weight of about 2 million. A very high molecular weight is rapidly obtained by enlarging the backbone of HMW units. The volume of subunits determined by microscopy is about $2 \cdot 10^{-5} \mu\text{m}^3$, so glutenin particles of the size of a B-starch kernel would contain about 70,000 molecular "Wieser units".

Considering the gluten strands visible at low magnification in dough (Fig. 90 and Fig. 91), a lot of molecules have to stick together in order to produce the large extensible elastic structures.

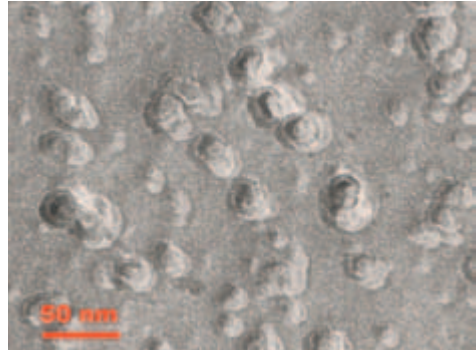


Fig. 88: Transmission electron micrograph of high molecular weight subunits (HMW; 2% in 0.05 mol/L acetic acid).

We do not know if this is done only by secondary forces like hydrogen bonds or if molecules are entangled (Singh and MacRitchie, 2001), nor if the latter is already done in the protein bodies of the endosperm cells. These cellular gluten bodies already have a dimension of up to 5 μm and spontaneously generate very long structures of glutenin when flour particles are put on a water surface (Fig. 90). But it is not unusual for globular proteins to unfold and spread on a water-to-air surface.

The filaments behave like the spokes of an umbrella. Between them there is a surface film of gliadin which we were able to remove, using a special technique with diluted ethanol. On the addition of water the glutenin filaments contracted and took on an irregular shape (Fig. 91). We were able to demonstrate the elastic character and high cohesiveness of the

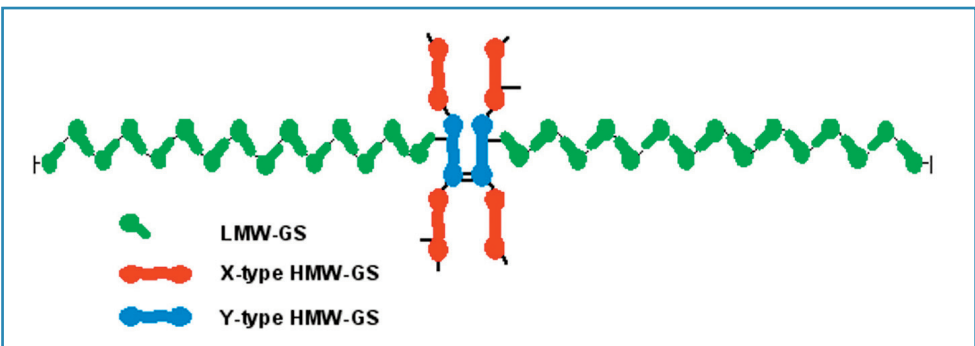


Fig. 89: Wieser model of a basic molecular unit of glutenin with the three types of subunits (LMW/HMW = low/high molecular weight; GS = glutenin subunit)

gluten in filaments. When stirred with a glass capillary the filaments easily stick together and form big lumps of gluten.

Different lumps or filaments spontaneously stick together when they come into contact, forming large gluten structures. This must occur in the unmixed flour system (Unbehend *et al.*, 2004). Gluten also aggregates without an input of mechanical energy and therefore without entanglements of glutenin. This results in a poorly extensible dough.

To obtain a more extensible dough, the structures arising from the endosperm cells of the flour particles have to be extended and disentangled in a kneader or mixer by high shear forces. The aligned glutenin structures will then interact at many more contact points and form bundles of filaments which may form entanglements again on relaxation.

14.11 Viscoelastic Deformation

Elastic and viscous deformation can be monitored by observing and drawing the filaments or bundles of filaments while these are immersed in the water droplet.

On extension beyond what is initially a purely elastic deformation the relaxation of the filaments begins, at first without a visible thinning of the strands. At greater elongation the thicker glutenin aggregates then slide along each other. They seem to be lubricated by a gliadin film covering their surface. This function of gliadin is probable, since the sliding movements are strongly accelerated

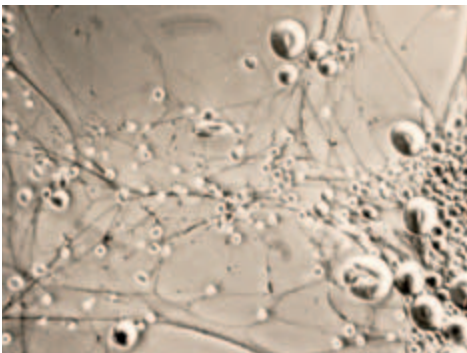


Fig. 90: Gluten structures issuing from a flour particle on a water surface.

when pure isolated gliadin is added to dough. At further elongation the filaments become thin and rupture. The ends of the filaments contract to a globular shape, adopting the smallest possible surface because of surface tension. Surface tension is also the reason why gluten forms in water and dough, not gluten membranes enveloping gas bubbles. These microscopic studies on gluten filaments demonstrate what happens in dough. They explain why there is a measurable elasticity and why its amount is not related to volume expansion.

Dough extends elastically in the first stage of proof, then on further inflation it will begin to flow until the strands of the gluten network become too thin and rupture. The moment of rupture and the maximum volume at a given good shape of the dough piece will depend on the initial diameter of the strands and the continuity of the structures. That means they will depend on the cohesiveness of the gluten.

14.12 Elasticity: a Must for Wheat Dough?

Our studies have shown that the intensity of elastic behaviour depends on the method of determination and does not correlate with baked volume. Elasticity may only be an overestimated phenomenon accompanying the other physical parameters, which are viscosity and cohesiveness. The latter for instance, being highly correlated to the degree of rupture of the gluten network, or in other

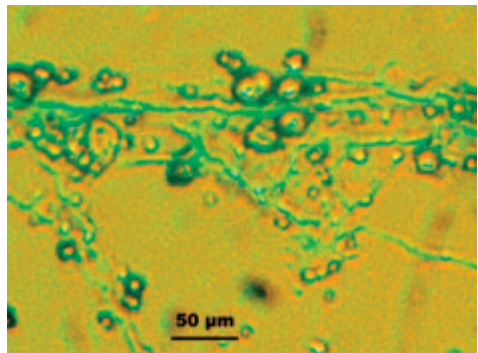


Fig. 91: Glutenin filaments (stained green) separated from gliadin.

words to the maximum volume, is of immense importance.

Elasticity, which is closely connected to the cohesive structures, seems to be nothing but an indicator of a persisting good continuous gluten network. The fingerprint method for testing the degree of maturation of dough is an example. But when we think of elasticity we always have in mind a round balloon inflated by air. Is elasticity at least the reason for the rounded bread shape? Or can we also get a good shape with non-elastic materials that support dough stability? Such a material has yet to be found.

14.13 References

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