13 Fundamentals of Rheology and Spectrometry

13.1 Rheology

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13.1.1 Introduction

Bread in all its diversity has existed for over 6,000 years; rheology as a branch of physics is a great deal younger, though scarcely less diverse. What, then, is the relationship between bread and the rheology of dough? Descriptions of the first attempts to measure the physical properties of food in general and of bread doughs in particular date back to the 18th century, when Beccari assessed the quality and structure of wheat doughs sensorily in 1728 and Bolland and Kunis later carried out tests with the Aleurometer in 1836 and 1885 respectively. Dough rheology as we know it today did not originate until the early 20th century and was born of necessity. Hungary was considered the granary of the Austro-Hungarian Empire and exported wheat to the rest of Europe. The Hungarian wheat varieties were popular in North America too – some were in fact related to the American varieties, having common parents. Hungarian wheat was much in demand for its quality. So the breeders made every effort to cultivate and grow higher-yielding varieties. But the quality of these new wheat varieties no longer met the requirements of the market. In order to assess the baking properties of wheat varieties or wheat lots without performing expensive and time-consuming baking trials, the first recording mixers (Hankoczy) and dough stretching instruments (Hankoczy, Rejtö, Gruzl) were constructed in the early 20th century; they may be regarded as the forerunners of the Swanson Working Mixograph in America and also the Brabender Farinograph and Extensograph and the Chopin Alveograph in Europe. After World War II the situation changed in that in Germany the Brabender Farinograph and Extensograph were used to determine the suitability of the quality wheat lots imported from North America (USA and Canada) and South America (Argentina). The Alveograph was used from the start to compare and check the quality of flour batches. An interesting description of this development is given by Muller and Wassermann (Muller, 1964 and 1966; Wassermann, 1993).

The last four measuring instruments – the Farinograph, Mixograph, Extensograph and Alveograph – are used virtually unchanged to this day in the service of the science and practical task of cereal processing. However, they use relatively strong deformation forces as a measuring principle, and they only describe the properties of the dough in the cold phase of the bread-making process, during mixing and after fermentation. These two points may be regarded as disadvantages. The pasting properties of the cereal starch as a function of alpha-amylase activity at high temperatures similar to those of an oven have been determined with the Brabender Amylograph and the Hagberg-Perten Falling Number instrument since the 1920s and 1960s respectively, and more recently with the Newport Scientific Rapid Visco Analyzer. For technical reasons these measurements can only be made in flour/water slurries of various concentrations.

In the early 1930s, Scott Blair laid the foundations of fundamental rheometry and rheology of food by measuring and describing the viscoelastic properties of wheat dough (Schofield and Blair, 1932). During the 1970s and 1980s, fundamental rheology experienced a major upswing with the construction of new, precise and sensitive instruments whose measurements permitted an insight into the structures and behaviour of foods. These new rheometers apply the dynamic, oscillating mode as a measuring principle, with which they can simultaneously record complex viscosity and its components elasticity and plasticity ("pure viscosity"). Moreover, the deformation forces they apply are extremely small; since these do not interfere with the structure of the specimens, they permit continuous monitoring of changes in the viscoelastic properties of a dough as a function of time and temperature. This is really the basis of the simulating "recording baking trial" which makes it possible to monitor the changes in the viscoelastic properties of the dough in the baker's oven (Weipert, 1987 and 1992).

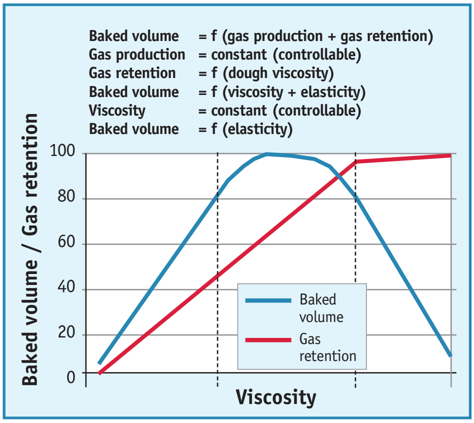
Bread baking is ultimately a process of the uptake and binding of water by the swelling substances (such as proteins and pentosans) in the dough and the rebinding of water by the pasted starch in the heated, baked dough or the crumb of the bread which results in changes in the viscosity or consistency of the dough or bread crumb and can therefore be demonstrated well by rheometry. In other words: rheology in general and rheometry in particular are good tools for studying, interpreting, predicting and checking baking properties.

13.1.2 Viscosity and Elasticity of Dough

When mixed with water the flour becomes dough, a cohesive mass in which the gluten forms a three-dimensional network made up of strands and membranes in which the starch granules are embedded (Amend, 1996 and Bloksma, 1990). The viscosity or consistency of the dough depends on the amount of water and other ingredients added, but also on the intensity of mixing. The expansion and volume of the baked products as a quality attribute of the flour is the result of the production and retention of gas. In this context the viscosity or consistency of the dough is initially the main characteristic that determines the gas retention necessary for making up a flour into bread and other products. The baker will strive to achieve an optimum consistency which is thick enough to make the dough workable (kneading, moulding) and ensure that it keeps its shape and on the other hand thin enough to allow the carbon dioxide generated by the yeast to cause the expansion that results in the desired leavening of the dough and its baked volume. It was established only recently that a dough can come about as a "hydrated, unmixed flour system" through aggregation of the gluten proteins without an input of energy from mixing. Its physical, rheological properties are somewhat different from those of doughs produced by mixing; it is firmer and less extensible, has a high initial viscosity and elasticity but low stability (Unbehend, 2002). Nevertheless, mixing is likely to remain indispensable, for the air bubbles introduced into the dough by mixing and in which the carbon dioxide collects during fermentation are the "starting point" for the pores that result in the baked volume of the products (Hoseney, 1986).

Doughs without Mixing

Efforts to minimize the energy input necessary for making up a dough have led to the development of the new Rapidojet technique. On the basis of observations by Amend (1996), Noll (2002) came to the same conclusion as Unbehend (2002), namely that far less energy is needed for preparing dough than is normally used in bakeries. With the Rapidojet, Noll developed a fast method of dough preparation that saves space, time and above all energy. Air and water are introduced at high pressure into a stream of flour running into a pipe. Within seconds this results in a dough that has



Dough characteristics

Soft, weak	Normal for baking	Firm, short
Mainly inelastic, plastic	Rheologically balanced, extensibly elastic	Mainly elastic
Viscoelastic	Viscoelastic	Elastoviscous

Fig. 53: Baked volume as a function of viscosity and viscoelastic dough properties

viscoelastic properties similar to those of doughs produced by mixing and is just as easy to make up into bread. The energy introduced by the pressure of the added water is much less than that normally required by bakeries (Noll, 2002).

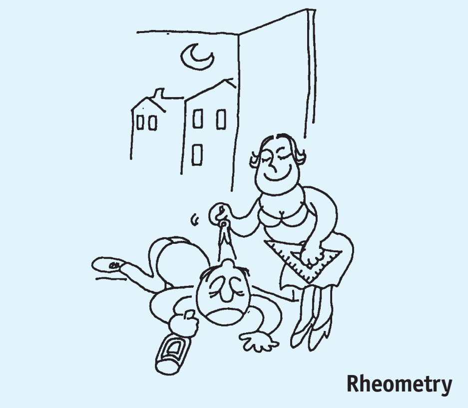
If we view the bread-making process as an interaction of gas production and gas retention it may be said that gas production can be adjusted, controlled and kept constant with the amount of yeast in the formulation, the quantity of the fermentable sugars maltose and glucose added or present and other technical measures such as fermentation temperature and time. There remains gas retention as a factor that demands the baker's attention and technical skill (Fig. 53). If we assume that gas retention depends directly on the consistency of the dough, we may expect gas retention to increase in proportion to consistency. This holds true in practice: firm doughs with a high gas retention capacity combined with good gas production result in a high volume yield. Conversely it is logical that the low gas retention capacity of doughs with low viscosity (consistency) results in a low volume yield. Because of their gluten structure the soft and sometimes weak doughs are permeable to gas. It is also logical that very firm, short or "bucky" doughs are too strong to be stretched by the developing carbon dioxide because of their firmness and stability. The result is a low volume yield.

This means that an optimum viscosity or consistency of the dough is desirable in order to ensure the highest possible volume yield. Since this factor can be adjusted and controlled by determining water absorption with the Farinograph, it may also be regarded as constant. The viscoelastic properties of the dough, generally known by bakers and cereal processors as "dough characteristics", vary from soft and weak to firm and short; it is the "normal" dough characteristics that bring the best results in each case. The volume of the baked products is therefore a function of viscosity and elasticity. If the viscosity can be adjusted (by adding water) and may therefore be regarded as a constant factor, it is ultimately elasticity or the rheological balance between extensibility and elasticity that determines the value of a wheat flour for baking. Too much elasticity results in short, bucky doughs; too little makes the doughs soft and weak. Dough rheology makes it possible to identify these variety-related properties – viscosity and elasticity – quickly and reliably. We also know ways and means by which the viscoelastic properties can be altered and optimized to a certain extent; here, especially, rheometry helps with dosing and control.

The objective and purpose of rheology is to identify the basic rheological properties of substances and interpret the changes in these under defined measurement conditions.

Basic rheological properties are:

- strength (solidity),
- viscosity,
- elasticity, and
- plasticity.

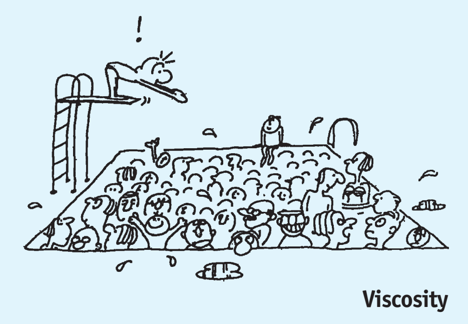


To establish these properties, rheometry – a sub-discipline of rheology – uses a deformation force and measures the effect of this force on the specimen (in this case the dough) as its deformation. The deformation force may be great or small; the measurement will vary accordingly.

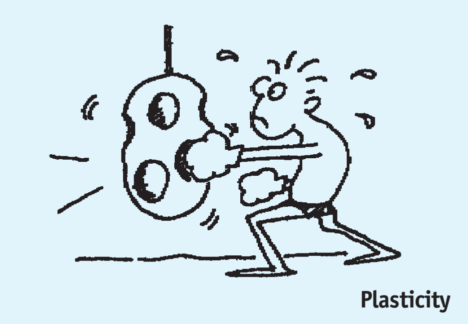
Strength as a further property of a material is easy to determine. A body, as rheologists call the substance to be tested, is a viscous mass or a fluid if it has no yield point, flows by its own gravity and is therefore not dimensionally stable. By contrast a solid (solid body) keeps its shape, can only be made to flow by the effect of a deformation force and has a yield point. A solid can also be a plastic, elastic or viscoelastic body, depending on its structure.

Viscosity is an important characteristic of any material; it is made up of the components elasticity and "pure viscosity" or plasticity. In the case of liquids, viscosity may be described as the internal friction between the molecules and molecular aggregates; in the case of solids it is the cohesion resulting from their structure. When determining basic properties it is possible to measure viscosity (more precisely complex viscosity) and its component elasticity, whereas "plasticity" has to be calculated as an imaginary part of viscosity and the difference between the measured viscosity and elasticity. A body is termed elastic if it is difficult to deform and regains its original shape when the deformation force has ceased to act on it. Deformation was then reversible and the deformation energy applied was stored. If, on the other hand, a body is easy to deform and remains deformed after the deformation force has ceased to act, the body is irreversibly plastic and the deformation energy has been lost.

The directly measurable and determinable basic properties "viscosity" and "elasticity" would therefore seem to be the most important characteristics for describing a material and for its behaviour as a raw material, in the process itself and finally as an end product. That is why dough rheology gives special attention to these two properties. The materials known to us, including foods, have mainly viscoelastic properties, and the characteristics elasticity and plasticity occur in different ratios to each other.


Viscosity


Elasticity


Plasticity


Viscoelasticity

13.1.3 Two Kinds of Rheometry

Our modern way of life is unimaginable without rheometry. Rheometry is used to predict the avalanche menace in ski-fields, to minimize the risk of a heart attack by measuring and influencing the flow properties of blood, to estimate the weight-bearing capacity of shopping bags made from petropolymers or bio-polymers, and even to increase the service speed of tennis cracks by developing the right strings for their rackets. Rheology has a multitude of uses and is all around us. In food production it is used to assess the quality of raw materials and end products, and it has therefore become an important and powerful aid to food technologists. It also aims to determine the texture of foods and thus replace sensory testing in the judgement of quality. But the latter is hardly likely to succeed, partly because there are no suitable measuring techniques so far, and partly because experienced technologists of long standing are unlikely to allow themselves to be ousted or challenged by measuring instruments.

Rheology has a sub-discipline, rheometry, whose task is to make and explain measurements. We speak of ***empirical*** (also known as descriptive or imitative) rheometry and ***fundamental*** (absolute) rheometry, depending on the measuring principle and the possibilities offered by the instruments used. Empirical rheometry may also be termed conventional rheometry. From the point of view of rheologists and practical users, both groups of instruments and measuring techniques have advantages and disadvantages, most of which result from the design of the instruments and the measuring principle. The users and advocates of the two different rheometries regard each other with suspicion. One rheologist has described this situation aptly:

- **With the empirical methods we don't know what we are measuring, but it works;**
- **with the fundamental methods we know exactly what we are measuring, but it doesn't work.**

"It works" means that the measurements reflect the behaviour of a raw material during processing and also the quality of the end product. How the measurements are interpreted doubtless depends on the experience of the people who carry them out. In practice the measurements are often performed under conditions different from those of the process. Most of the instruments used in empirical rheometry are relics of the early days of dough rheology and have scarcely been modified to this day. They are very common, easy to use, and their results have found a permanent place in the terminology of cereal technologists.

The comment "but it doesn't work", said of fundamental rheometry years ago, has now ceased to apply. In the final decades of the last century, rheology in general experienced a considerable upswing with the development of new, versatile, sensitive, precise and efficient measuring instruments. These instruments were used chiefly in the plastics industry to demonstrate the structures of "noble" (and therefore expensive) thermoplastic polymer melts. Systematic work with measuring instruments of this kind yielded structural models for wheat and rye doughs too, and the biopolymer "dough" was found to conform to the same laws as the organic polymer melts. Moreover, it also undergoes phase transitions as it passes through the various temperature ranges. This discovery is not only of academic interest; it has also had practical value since the technique of freezing dough and heating pre-baked frozen dough portions became common practice at bakeries. But in spite of all the advantages of rheometers and fundamental rheometry, the high price of such measuring instruments and the more intricate work they require explain why they are not yet in general use in the laboratories of cereal processors. It is a sad fact that bread rolls are less lucrative than plastic polymer melts!

Being a branch of physics, rheology cannot quite do without mathematics; in some areas, in fact, it uses a great deal of mathematics and calculation. But that should not frighten us and prevent us from using rheometry. Rheology can manage without higher mathematics, especially when the results are considered in categories of "too much" or "too little" in relation to the desired optimum or used for drawing curves or diagrams. In the meantime simpler measuring instruments suitable for the routine work of cereal laboratories have come onto the market. Some combine the advantages of the two rheometries, overcome the old, strict divisions between empirical and fundamental rheometry, and are affordable into the bargain. So in future we may expect them to find their way into the research and development laboratories more often than in the past.

The use of rheometry in dough rheology has already been described in detail in the relevant standard methods (e.g. ICC, AACC, AOAC) and in textbooks on cereal technology. In our discussion of dough rheology and dough rheometry, their application in laboratories and interpretation of the results we do not intend to repeat this information. Our aim is to give "the practical man" an insight into what is going on backstage in nature and in the measuring instruments and dispel his fear of advanced science in an ivory tower.

13.1.4 Empirical Rheometry

Sensory Testing

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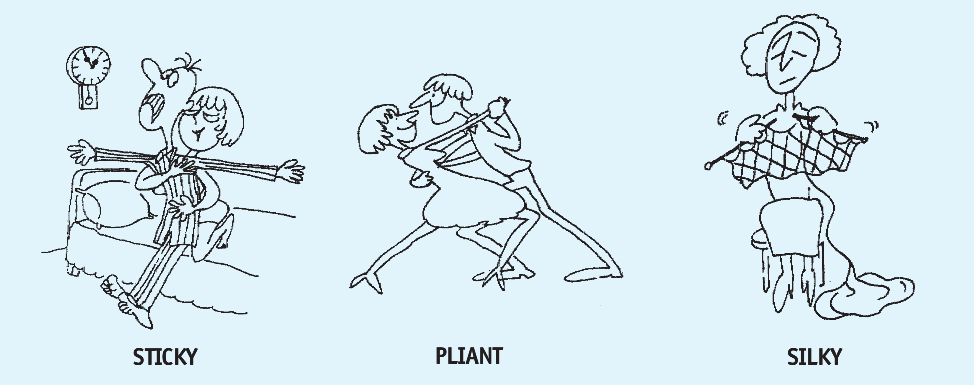
There can be no doubt that sensory testing to assess the characteristics of dough and the crumb and crust of bread is one of the classic and oldest uses of empirical rheometry. The baker uses his hand and his acquired experience to judge the viscosity and elastic properties of his intermediate product (the dough) and his end product (the crumb of the bread). A baker's tester (a specialist trained in sensory testing) works almost like an instrument; both the production manager and the customer rely on his "measurements". A tester assesses the nature of the dough according to its components: "elasticity" (from unsatisfactory and soft to short) and "surface" (from slimy and wet to dry). He assesses the crumb according to elasticity and chewability; his verdict can range from "soft" to "firm". A baker's language is more flowery and describes the viscoelastic properties of the dough more aptly. He would distinguish more precisely between "soft" and "weak" on the one hand and "firm" on the other by describing the dough as "sticky", "pliant" or "pliable", "silky" or even "bucky" (if it "springs back").



Semantic description of dough properties

These ratings describe the desirable, positive characteristics of the dough and its undesirable, negative characteristics. In their flowery terms they also describe the shred of an RMT [17] roll. The shred of an RMT roll is an important indicator of the viscoelastic properties of the dough, and vice versa. The shape of the shred and the appearance of the roll can be predicted from the known properties of the dough. A dough portion shaped by flattening and rolling in the RMT standard baking test should open up in the oven to form a "normal" shred.

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[17] Rapid Mix Test; chapter 12.9.3 page 115

In the case of doughs with short, dry properties the shred tends to be wide open; besides genetic and environmental factors the causes of this may be unsuitable drying and heat damage to wheat that has been harvested wet. A "sewn up" roll with a shred that is stuck together and unopened is the result of a wet dough surface. An unopened shred in a small, irregularly shaped roll in which the baker's fingers have left clearly visible marks may indicate weak flour quality. In conjunction with a large baked volume the unopened shred shows that the flour has quality reserves; such flour can be used for blending with and improving flours of weak quality. The conclusions drawn from the quality characteristic "shred" in the RMT standard baking test can also be applied to loaves of bread and other baked products.

The ratings acquired by sensory testing are underpinned by measurements carried out on doughs with the Farinograph and the Extensograph. These instruments of empirical rheometry are used in large mills and industrial bakeries.

To a certain extent a baker can correct his dough, made with a small amount of flour, in the course of preparation. But an industrial bakery must have formulations it can rely on; they must ensure that the products turn out properly, since no corrections can be made to a large batch of dough. For large-scale baking, objective measurements of the physical and rheological properties of the dough are essential. Results obtained by empirical rheometry are used effectively for this purpose too.

Instruments of Empirical Rheology

As we know, the process of bread making consists of two phases: a cold phase in which the dough is prepared by mixing and left to ferment, and a hot phase in which the dough is transformed into bread in the oven. Monitoring the process means showing and checking the viscosity and viscoelastic properties in both phases. For technical reasons empirical rheometry can only carry out the measurements separately.

In the Cold Phase of Bread Making

Bread baking starts with mixing flour and water to form a dough, followed by fermentation ("rising") in a fermentation chamber at controlled, slightly elevated temperatures similar to those used in practice. Mixing and kneading is simulated with recording mixers under laboratory conditions; the condition of the dough during and after fermentation is shown and described by means of stretching tests. The experience of the baker (laboratory worker, production manager, shift supervisor) enables him to read the measurements and curves thus obtained in order to determine the optimum flour for a particular product and adjust the recipe accordingly.

Recording Mixers

Generally speaking, modern laboratories use two types of recording mixer: the Brabender Farinograph and the Swanson Working Mixograph. These two mixers differ fundamentally in the way they mix and thus the mechanical stress to which the dough is exposed, i.e. in the ratio of flour to water and the amount of water added at the start of mixing. The sigma-shaped paddles of the Farinograph squeeze and stress the dough relatively little compared to other types of mixer (Weipert, 1987b). The amount of water that has to be added to achieve a constant consistency of the dough is determined in a preliminary test before the main test. The working parts of the Mixograph are vertical pins that exercise a planetary, rotating motion and stretch, squeeze and fold the dough; mixing of this kind subjects the dough to greater mechanical stress than that of the Farinograh mixer. The doughs are prepared with the same amount of added water irrespective of the water absorption capacity of the flours. This means that evaluation and interpretation of the curves resulting from the measurements differs. For the sake of completeness it should be said at this point that the one-arm Alveograph mixer stresses the dough less than the Farinograph. With their sharp-edged tools, which result in very intensive mechanical stress, the mixers of the Brabender Do-Corder and the Resistograph damage the dough to the point where it completely loses its structure ("fatigue point"). It is deformed until it becomes liquid and is literally destroyed.

Farinograph

The recording, reading and analysis of a Farinogram, the curve of measurements obtained with a Farinograph, is described by the recommendations of the manufacturer Brabender, the Farinograph manual (D'Appolonia and Kunerth, 1984) – a study of the use of the Farinograph – and finally stipulated by the standard methods (ICC; AOAC).

115 In the bowl of a Farinograph the flour is mixed with the water to form a dough; the dough is then developed mechanically and weakened mechanically by over-mixing until its structure is destroyed. This procedure is measured and recorded as kneading resistance in the form of torque by means of a dynamometer; the recorded curve is therefore a force/time diagram from which the work or energy input can be read off and calculated. The kneading resistance is assumed to be the viscosity of the dough, although the remaining properties of the dough such as its surface stickiness and adherence to the walls of the mixer and the paddles contribute quite considerably to the measured kneading resistance. In such tests this was most apparent with the wheat varieties that produced doughs with a very sticky surface; the water absorption capacity of these flours, which was high already, was increased even further, which made the dough softer and more sticky still. In cereal laboratories the viscosity of dough is often termed consistency. The viscosity or consistency of the dough is stated in the Farinogram in relative units (FU) specific to the Farinograph, on a scale from 0 to 1,000 FU.

In practical baking, determination of viscosity in the Farinograph serves chiefly to establish the water absorption of a flour. This is the term for the amount of water that has to be added to a flour to achieve a viscosity of 500 FU. The water absorption of a flour depends on the latter's water-binding capacity and thus determines the yield of the dough and the amount of water to be added in the preparation of the dough. Besides the swelling substances in the wheat (proteins and pentosans), the mechanically damaged starch granules also contribute to the water-binding capacity of a flour. The dough consistency of 500 FU is an empirical value felt to guarantee the best possible processing properties; it has been adopted in the RMT standard baking test for determining the amount of water to be added. Different dough consistencies have proved most suitable for some other types of baked products that require doughs of a soft or firm consistency.

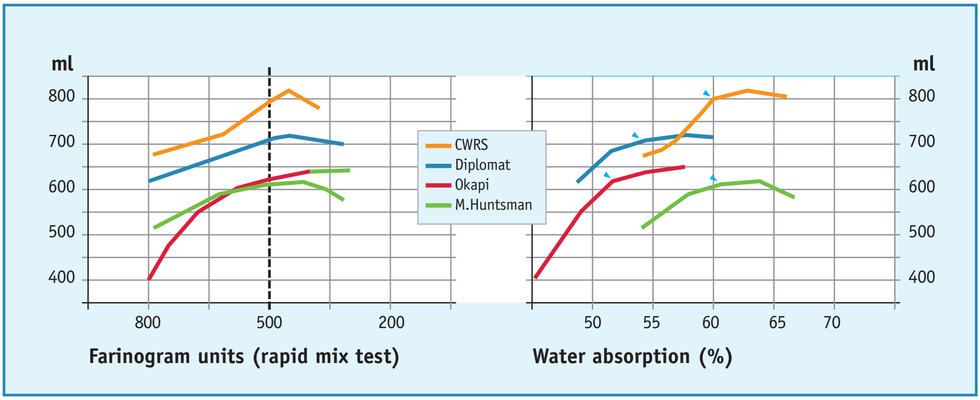

Fig. 54: Baked volume as a function of dough viscosity and water addition (the arrows indicate optimum water absorption as determined with the Farinograph).

The importance and benefit of determining water absorption in practical bread baking can be demonstrated by tests in which the amount of water added is increased or reduced by 5% or 10% as compared to the water absorption determined at 500 FU for four flours with different baking properties (Fig. 54). With all four flours a reduction of the amount of water added caused a noticeable thickening of the consistency of the dough in the Farinograph and resulted in a considerable fall in the volume yield of the baked product (in this case the bread rolls in the RMT standard baking test). As expected, the addition of more water resulted in a softer dough consistency, but the effect was initially a slight rise in the volume yield at a 5% increase in water absorption followed by a slight fall in the volume yield at 10% additional water. The flours showed differences in water absorption according to their quality, and the degree of their reactions to the different amounts of added water varied also. The fact that good wheat flours responded with increased baked volume to a higher dough yield or a softer dough is a sign that they have quality reserves. It also explains why some bread formulations require a larger amount of water, which would result in a Farinogram of 450 or even 400 FU. In terms of volume yield, one and the same amount of water led to different results in the products baked with the four flours; this again confirms the proposition that the viscoelastic properties of the dough are more important than its consistency.

A method has recently been developed which also makes it possible to determine the water absorption of rye flours (Brümmer, 1987). Since rye doughs react differently to mixing and rye flours result in a higher dough yield than wheat, the water absorption of rye flours or their optimum dough yield is read as viscosity after a mixing time of 10 min.

An analysis of a Farinogram shows the development time of the dough (up to reaching the 500 FU line), stability (unchanged structure of the dough without a fall in viscosity) and softening (fall in viscosity) at the end of the mixing time. Whereas the readings on the Y axis of the Farinogram, expressed in Farinograph units, denote viscosity and changes in viscosity during the mixing process, the width of the Farinogram curve is read as the elastic properties of the dough. This empirically based opinion of the cereal processors is correct with the reservation

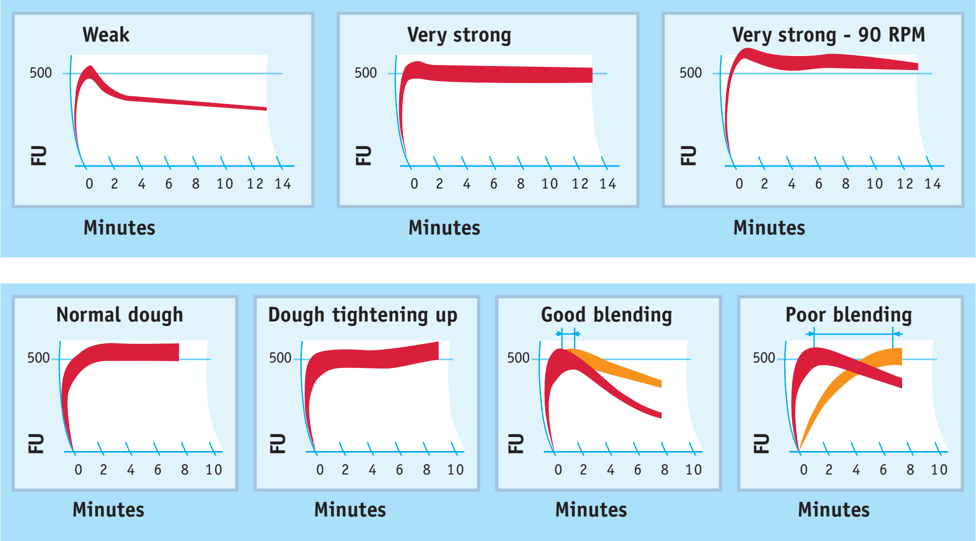

Fig. 55: Farinograms of weak and strong flour

that the width of the curve can be adjusted on the Farinograph itself and thus influenced; it is not an absolute value comparable from one instrument to another. The viscosity curve of the Farinogram gives information on the structure of the dough, its tolerance to kneading or the required input of mechanical energy and permits conclusions as to the intensity of mixing that is tolerable or necessary.

Wheat flours described by bakers as "weak" reach the 500 FU mark quickly and show no stability worth the name before undergoing a considerable decline in viscosity (Fig. 55). The "strong" flours take longer to develop before reaching the 500 FU line, where they remain for some time at good stability and then show only a minor decline in viscosity. The width of the curve for the two flours differs correspondingly. After reading off the dough development time and stability it is possible to decide how much mechanical development and energy input is needed. Such measurements support the theory of the specific energy input requirement of flours, which makes it possible to produce good-quality bread from weak flour if the latter's mixing requirements are taken into account (Frazier *et al.*, 1979).

124 There have always been "strong" flours whose Farinograms show a second peak after the dough development time; such cases have recently become more common, especially with unblended flours from certain newly bred wheat varieties. The standard method recommends reading this second peak as dough development time, but does not explain the reason for it. A glance at the structure of wheat gluten shows that it consists mainly of the fractions gliadin and glutenin (Hoseney, 1986). These two fractions differ considerably in respect of their molecular structure and functional properties (Fig. 56 and Fig. 57).

Fig. 56: Schematic representation and demonstration of the structure of gluten and its fractions, gliadin and glutenin

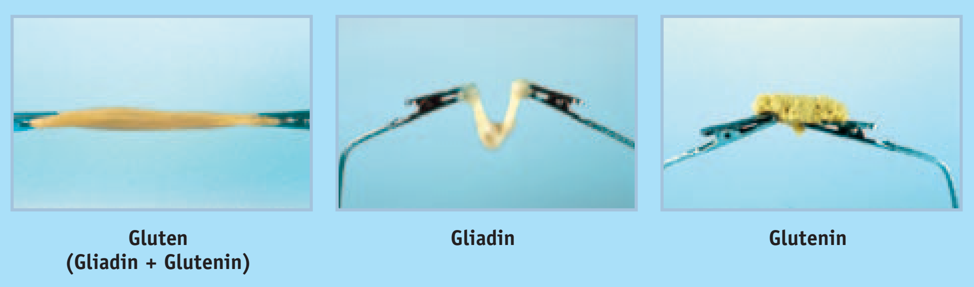

Fig. 57: Viscoelastic behaviour of rehydrated vital wheat gluten, gliadin and glutenin. (Photographs by Mühlenchemie GmbH & Co. KG. Commercial vital wheat gluten was suspended in 70% v/v ethanol and then centrifuged. The liquid phase was filtered through a filter paper. Solid and liquid phase were then dried at 40°C under vacuum, and rehydrated prior to the rheological demonstration.)

Whereas the insoluble fraction glutenin is known to form strand-like shapes called fibrils that give the gluten its firmness and elasticity, the gliadin fraction, which is soluble in alcohol, appears as a sticky mass and filler between the fibrils and only contributes to the viscosity of the gluten. Consequently, the viscoelastic behaviour of the gluten and the dough is closely bound up with the ratio of these two components. A weak flour (a C wheat[18] variety or a wheat lot with weak gluten) in which the functional properties of the gliadin fraction prevail will bind water quickly but in smaller amounts; it will form the dough faster but show a rapid fall in viscosity. A strong flour (an E or A variety or a wheat lot with strong gluten) in which the functional properties of the glutenin fraction prevail is characterized by a longer development time and longer stability. In a flour rich in protein or gluten the gliadin fraction present is initially responsible for the development of the dough (measured by achievement of the dough viscosity of 500 FU) together with part of the glutenin fraction, whereas a further part of the glutenin fraction requires more mechanical energy input and produces a second peak. This behaviour of doughs made from strong flour can be demonstrated by applying more mechanical energy (through faster mixing) in the Farinograph (Fig. 55). In this case the gliadin component of the dough is "developed" first but is soon weakened, whereas the glutenin component requires more energy for development and resists the mechanical energy during mixing. Such behaviour, known as stiffening, has already been observed under the standard conditions of the Farinograph method with some wheat varieties of American parentage. But similar behaviour is also found when flours of greatly differing quality are blended (as was observed years ago with the weak Maris Huntsman variety and very strong Canadian wheat of the CWRS class). On the basis of their Farinograms such blends have been rated poor, although such a combination of flours with greatly differing properties in the dough may result in a blend with very positive effects, as Extensograms show. Here too, the reason for such behaviour is the nature of the gluten fractions gliadin and glutenin, which depends on the variety, and their ratio in the gluten. And here too, the gliadin of the weak flour component results in early dough development and the glutenin of the strong flour component leads to stiffening. Although the ratio of the two gluten fractions is of genetic origin and thus a characteristic of the particular variety, it may be influenced by the environment; besides climatic conditions, such influences are chiefly the result of fertilizers. The properties of the gluten and the dough that are characteristic of the variety and may be influenced by the environment can be shown even more clearly with the Extensograph.

Besides water absorption, a Farinogram shows other quality characteristics of the dough such as development time, stability and softening; each of these provides important information in itself, but together they represent a multitude of data. To simplify the measurements the Valorigraph value was suggested at an early stage; it integrates these Farinogram characteristics in a single number. Read from the Farinogram by means of a special template, this value may lie between the theoretical figures 0 (for extremely weak flours) and 100 (for extremely strong flours). But these values can scarcely be achieved in practice; as a result, the method did not meet with acceptance in spite of some positive aspects. On the other hand the suggestion of reading a quality number (QN) off the Farinogram as the time taken for the viscosity (consistency) of the dough to fall by 30 FU after stability met with a positive response and has been introduced into the ICC standard method as one of the quality characteristics. This value integrates the development time and stability of the dough and indicates its softening; determination of the QN permits a faster but no less reliable evaluation of the Farinograms.

For various reasons the Mixograph has scarcely been used in Europe.

A new measuring instrument with a number of uses in the field of food rheology has recently been introduced: the Rheotec Multigraph. Like

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[18] *For German wheat classes see chapter 12.6.3 page 108*

the Farinograph, the instrument works on the principle of a recording mixer but with controlled heating of the dough. It records the changes in the viscosity (consistency) of the dough in the course of mixing and heating which reflect the effect of the proteins, starches and enzymes in the flour on the binding of water and the viscous properties of the dough. It might be said that such measurement is a kind of "recording baking test" (Sinaeve *et al.*, 2001). The method is based on the tests for the effect of additives and baking improvers on dough carried out by Nagao with a modified Farinograph (Tanaka *et al.*, 1980).

Stretching Methods – Extensograph versus Alveograph

127 During fermentation, the dough undergoes a process of inflation in which the carbon dioxide enlarges the pores and gives the dough greater volume. The gas retention capacity of a dough is therefore considered a quality characteristic and shown in the form of extension curves. As a displacement/time function the stretching of the fermenting dough may be regarded as a slight deformation, but for technical reasons the stretching tests in laboratories are carried out with greater deformation forces. For this reason such tests are rightly classified as empirical methods.

The principle of the stretching tests is that a dough made according to the standard method and prepared for extension is stretched and an extension curve recorded from which characteristics such as viscosity can be read directly and viscoelasticity indirectly. At present two stretching methods are in common use, carried out with fundamentally different measuring instruments and procedures. The methods were developed at the same time but independently of each other in regions with different wheat qualities and types of bread: the Chopin Alveograph in France and the Brabender Extensograph in Germany. Their predecessor was probably the Aleurograph and Laboragraph after Muller (1964 and 1966).

The extension curves in the Extensograph method (Extensograms) and in the Alveograph method (Alveograms) describe the extensional work (energy in the case of the Extensogram and W value in the case of the Alveogram) which is understood to be gas retention capacity (Faridi and Rasper, 1987, Rasper and Preston, 1991 and Weipert, 1993). In the further interpretation the height of the curve (R with the Extensogram and P value with the Alveogram) is understood as resistance to extension and the length of the curve read on the X axis (E with the Extensogram and L with the Alveogram) is taken to be extensibility. If resistance is now viewed in relation to extensibility, the quotients R/E = ratio and P/L describe the viscoelastic properties of the dough.

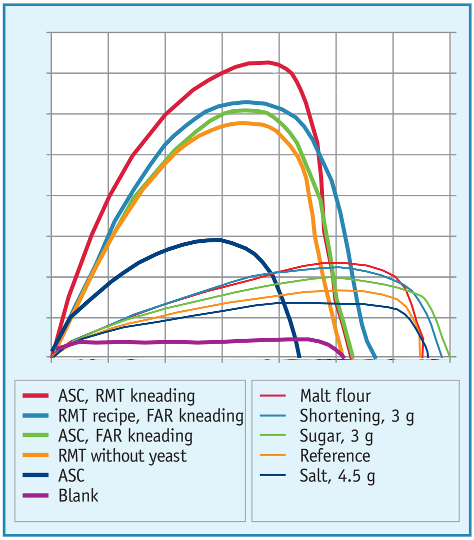
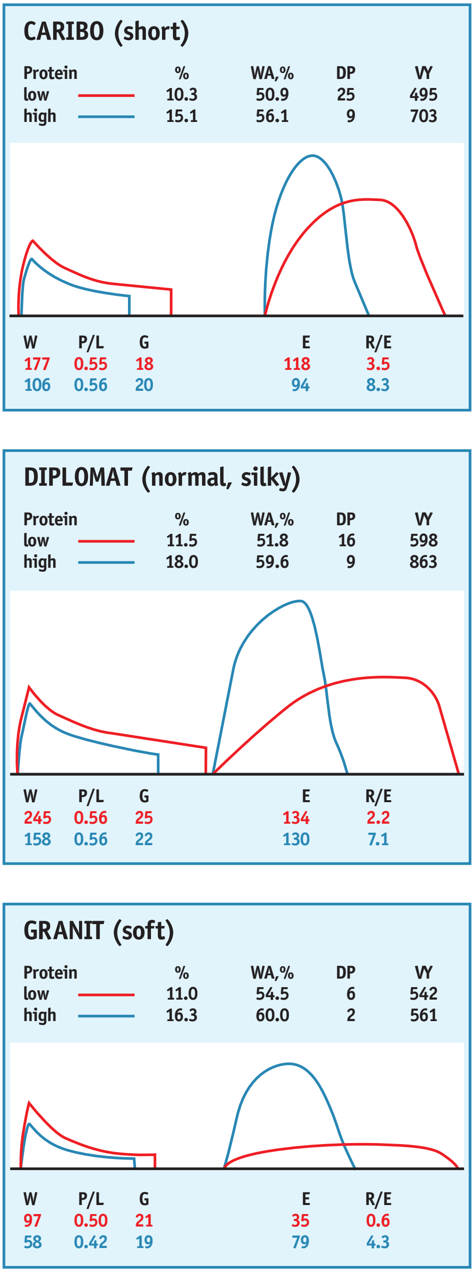


Fig. 58: Extensograms (135 min) of dough with different recipes and mixing processes (with and without salt, sugar, fat, malt flour, ascorbic acid; mixing in the Farinograph or Stephan mixer).
ASC - ascorbic acid
RMT - Rapid Mix Test
FAR - Farinograph

The question as to the usefulness of Extensograms and the reliability of the information they yield as a means of describing the visco-elastic properties of doughs has been answered by making Extensograms of unblended flours with different dough properties in various



CARIBO (short)

Protein		%	WA,%	DP	VY
low	🟥	10.3	50.9	25	495
high	🟦	15.1	56.1	9	703

W	P/L	G	E	R/E
177	0.55	18	118	3.5
106	0.56	20	94	8.3

DIPLOMAT (normal, silky)

Protein		%	WA,%	DP	VY
low	🟥	11.5	51.8	16	598
high	🟦	18.0	59.6	9	863

W	P/L	G	E	R/E
245	0.56	25	134	2.2
158	0.56	22	130	7.1

GRANIT (soft)

Protein		%	WA,%	DP	VY
low	🟥	11.0	54.5	6	542
high	🟦	16.3	60.0	2	561

W	P/L	G	E	R/E
97	0.50	21	35	0.6
58	0.42	19	79	4.3

Fig. 59: Alveograms and Extensograms of wheat flour with different dough properties and protein content.
WA = Water Absorption by Farinograph
DP = Dough Property Index (1 = soft, slack, sticky, 25 = short and dry; about 9 is normal and desirable)
VY = Volume Yield in RMT baking trial mL/100 g flour

different formulations and using different methods of preparation (Bolling and Weipert, 1984). The Extensograms reacted very sensitively to the changes in the formulation, the individual ingredients added to the flour in the RMT standard baking test (salt, ascorbic acid, fat, malt flour, sugar) having a characteristic effect on the curve of the Extensograms (Fig. 58). Even the ascorbic acid alone had a very strong effect. The interaction of all the ingredients in the RMT formulation with the flour showed itself in the Extensogram with the largest area; preparation of the dough in the Farinograph or in the Stephan mixer during the RMT standard baking test made no appreciable difference to the curves of the Extensograms. The most important result was that the Extensogram made with salt and ascorbic acid according to the standard method was found to be practically identical to the Extensogram of the RMT dough (complete formulation but without yeast). This confirms and justifies the Extensogram method as a practical and informative procedure.

Extensograms are indeed capable of expressing the quality of a flour and its suitability for making different bakery items. Using flours from three different wheat varieties with extremely different dough properties (short, normal, soft), each with two different protein levels (low and high), it was possible to demonstrate that Extensograms show both the variety-related quality of the wheat flours and the influence of nitrogen fertilizers (Fig. 59). The Extensograms differentiated clearly between the flours at both protein levels. This could be seen both from the energy values (area below the curve) and from the ratios (R/E). At a low protein content the Extensograms of all three varieties showed higher resistance and lower extensibility, thus indicating flours with shorter dough properties. This was especially evident in the variety with genetically short dough properties. At high protein levels, all three varieties produced Extensograms with lower resistance but higher extensibility, indicating softer dough properties; again this was especially evident

131 in the variety with genetically short dough properties. In the variety with the "normal" dough properties an increase in the protein content of the flour resulted in slightly reduced resistance and increased extensibility, but in both cases the Extensogram data – including energy and the ratio – indicated good quality which was enhanced further by the protein increase. The energy values and ratios of all the Extensograms were in line with the baked volumes achieved with these flours. The low energy values in conjunction with low ratios (0.6) that indicated soft and weak doughs and the high ratios (7 and above) in conjunction with low energy values that stand for short doughs were confirmed by low baked volumes. High energy values and ratios in the optimum range (about 1.5 to 3.0) in the Extensograms indicated a flour of good quality and high baked volumes (Weipert, 1981, 1992 and 1993).

132 The Alveograms recorded at the same time and with the same flours did not distinguish so clearly between the various flour qualities. Although some differences were found in the W values, the P/L ratio was virtually identical in all the Alveograms (0.42 - 0.56); this made it impossible to read off differences in the dough properties. A recommended procedure for determining the elastic properties of a dough directly with the Alveograph is to carry out a second test, a pressure relaxation test, in which the air pressure suddenly stops after the formation of the dough bubble and the relaxation of the dough is read off from the resulting curve (Faridi and Rasper, 1987). This measurement procedure was developed on the lines of the creep recovery or stress relaxation graphs used in fundamental rheometry and recorded with a rotating viscometer or rheometer (Fig. 63). However, this measurement method has not established itself in practical testing with the Alveograph.

129 The reasons why the extension curves of the Extensogram and the Alveogram yield different information lie in the way the tests are carried out. The most important, most fundamental and decisive difference between the two ICC standard methods is already to be found in the preparation of the dough. The Alveograph method uses a constant amount of water, which naturally results in doughs of different consistency; the Extensograph method assumes that the doughs are of constant consistency following determination of optimum water absorption in the Farinograph. If the two methods are assumed to describe the rheological properties of the dough for processing in the bakehouse, the Alveograph method records a condition of the dough that is far removed from its actual rheological condition at the time of processing into bread or other products because of the addition of a constant amount of water irrespective of the quality of the flour; this amount is in any case far too small for bakers' doughs. The constant amount of water added to the Alveograph doughs corresponds to a water absorption of 50% for all flours irrespective of their quality, whereas today's wheat flours have a water absorption capacity between 54% and over 60% and are processed into bread at these water absorptions, or at the corresponding dough yields. We should not forget that water is a "plasticizer" that makes the dough softer but optimizes its consistency if properly dosed and ensures good baked results when combined with flour improvers or other ingredients. With the addition of 50% or 58% water, for example, depending on its water absorption, one and the same flour yields dough with greatly differing rheological properties, viscosity and elasticity (Fig. 54).

The other difference in dough preparation between the two methods (nature and duration of mixing) is not so fundamentally important. In the Alveograph the measurement itself is performed by bi-axial stretching, carried out by inflating a piece of dough into a bubble with an air pump until it bursts. In the Extensograph it is done by uni-axial, linear stretching of a strip of dough with a hook until it breaks. The speed of deformation is similar for the two methods; in the Extensograph it is 1.5 cm/s. But although the resulting measurements, the recorded curves, are supposed to provide the same information, they have come about differently. The Alveogram shows the pressure curve of the air trapped in the dough bubble, whereas the Extensogram is a deformation curve from which the resistance to extension (a measure of strength or even the elastic component) and extensibility (as the compliant, plastic component of the dough properties) can be read off. The maximum pressure in the Alveogram, the P value, that denotes strength, actually shows the yield point of the dough, i.e. the force that has to be exerted in order to start stretching the gluten fibrils in a dough. This P value serves to estimate the dough yield or the amount of water to be added. But a pressure curve is very different from a deformation curve. A deformation curve can be obtained by recording the increase in volume of the expanding dough bubble in a vertical direction (Fig. 62).

A further difference between the two methods which is often neglected lies in the time factor, or the duration of the test. An Alveogram is recorded 28 minutes after the start of mixing; for technical reasons only one measurement can be performed on each dough specimen (Faridi and Rasper, 1987). An Extensograph test usually consists of three Extensograms made at intervals of 45 minutes during the dough resting time. This time factor is important for two reasons and must not be ignored. Kneading and moulding for the test cause a "structural activation" of the dough during which the mechanical energy of the mixing and moulding is "stored" in the elastic component and greatly influences the result of the measurement (Rasper and Preston, 1991 and Weipert, 1981). In this state, resistance to extension is higher and extensibility lower. The stored energy subsides after about 45 - 60 minutes; the taut "springs" of elasticity relax during this time and the dough undergoes a structural relaxation or structural recovery so that its "real, uninfluenced" rheological properties can be measured. The stretching of a dough resulting from inflation and an increase in volume during fermentation and in the early part of the oven phase take place in a relaxed state. Moreover, the effect of the ascorbic acid, enzymes and emulsifiers added as flour improvers or baking ingredients can naturally be identified better after a longer time of action than after a short one. This effect is therefore only visible to a certain extent in Alveograms (Weipert, 1981 and 1992).

When evaluating the extension curves of Alveograms and Extensograms it is necessary to take all these factors into consideration. Only then can the right conclusions be drawn concerning the properties of the flours and their suitability for certain baking purposes. Besides determining the viscosity of a dough it is also extremely important to establish its viscoelastic properties. An Extensogram reveals both the viscosity and the viscoelasticity of a flour as a genetic characteristic of the variety and as the influence of the environment – chiefly the supply of nutrients and the use of fertilizers (Fig. 59). It was evident that the Extensograms had clearly recognized and expressed the dough properties of the wheat varieties, described as short, normal or soft (Weipert, 1992 and 1993). This was especially apparent in flours with a low protein content. Protein levels in the flour that had been raised by nitrogen fertilizers increased the extensibility of the dough; the Extensograms of the wheat variety with genetically short dough properties therefore showed normal dough properties with balanced viscoelasticity at higher protein levels. The variety with normal dough properties retained these properties even at a higher protein level, but its energy value (area below the curve) was greater; the soft dough properties of the soft variety became softer still. The softening of the dough properties, known by bakers as suppleness or pliancy, is explained by the increase in the reserve protein component of the gluten, the gliadin. Nitrogen fertilization causes more of this component than of the glutenin component to be formed and stored. But in a dry, warm climate, more glutenin is stored in the wheat grain, and this results in wheat with dry, short dough properties. Unlike glutenin, that determines the strength and therefore the elastic behaviour of the gluten and the dough by forming strands and membranes as well as binding large amounts of water, the gliadin component of the gluten

2 only contributes to the viscosity (consistency, water binding capacity) of the gluten and the dough. Besides nitrogen fertilization, cooler and wetter environmental conditions favour the formation of gliadin and result in softer, pliant doughs.

The functional properties and interaction of the two components, gliadin and glutenin, have been explained very clearly by Hoseney (1986; Fig. 56). As the photograph shows (Fig. 57), the pure gliadin obtained by washing out and isolation is sticky and highly extensible; the pure glutenin is firm, elastic and difficult to deform. It is the ratio and functional properties of these two components of the gluten that determine the latter's viscoelastic properties and thus the rheological properties of the dough. These properties can be deduced from the Farinogram, but they are more apparent in an extension curve like the Extensogram.

Without wishing to question the usefulness of the Alveograph method we have to admit, on the basis of these examples, that the pattern and individual characteristic data of the Alveograms do not reveal the dough properties of the varieties and the ways in which they are changed by higher protein levels in the flour – i.e. their current quality. The reasons for this have already been discussed. For the sake of completeness we should mention that the necessity of determining optimum water absorption has been recognized even by the supporters of the Alveograph, and that a method of determining water absorption with the Alveograph mixer was recently presented (see chapter on Modern Cereal Analysis). Unfortunately it is still not possible to apply the water absorption determined in this way as the amount of water needed to prepare the dough for the Alveogram recording and thus to indicate the rheological properties of the dough with dough consistencies close to those used in practice. The biaxial stretching test is not fundamentally unsuitable as a measurement method, as Dobraszcyk has shown (Dobraszcyk, 2002). At the time of its development and use in France the Alveograph method was a suitable means of characterizing flour: the flours obtained from wheat varieties with a soft grain structure and with a low protein content and water absorption could be described and compared well from one lot to the next by means of Alveograms. But now that even in France the trend in wheat breeding is towards varieties with a hard grain structure (which may result in mechanical damage to the starch grains during grinding) and flours with higher protein levels and thus greater water absorption, efforts are being made to adjust the Alveograph method to the new wheat qualities. 132

The advantages of the Extensograph method in showing the "rheological" behaviour of doughs at a consistency such as is used in the production of very different types of baked goods have been used to define the term "rheological optimum" (Schäfer, 1972). Schäfer suggested taking this to mean the state of the dough most suitable for producing a bakery item, which would naturally ensure the best results during baking and an end product of the desired quality. The requirement for this state is doubtless optimum quality of the flour, but it can be influenced and controlled by flour improvers and ingredients that act on the properties of the dough. For this purpose there are product ranges offering a choice of emulsifiers and enzyme preparations designed to achieve the rheological optimum and enhance the final result of baking. A further practical application of the rheological optimum lies in the controlled treatment of flours with ascorbic acid at the mill and with enzyme preparations (amylase, proteases, pentosanases, xylanases) and other flour-improving ingredients based on lecithin, cystine, cysteine and emulsifiers, which result in better inflation of the dough, increased water absorption and ultimately better flavour and prolonged shelf life of the baked products. 128

In practice, a flour can be optimized in respect of its baking properties at a mill by blending flours with different dough properties. In a flour blend the energy values of the Extensograms of the two flours making up the blend are combined. The energy value of the blend lies between the values for the components in accordance with their ratio in the mixture. But the volume yield as a quality characteristic of the baked product is higher than that calculated from the individual volume yields of the blended components (Bolling, 1980). This effect is due to optimization of the viscoelastic properties of the flour blend and is therefore recognizable from the ratio R/E, which is within the optimum and desired range of the Extensogram for the blend. This value increases with the extent of the difference between the dough properties "short" and "soft" of the components of the blend, which ultimately result in "normal" dough properties and achievement of a rheological optimum (Schäfer, 1972). But this does not mean that any arbitrary flour blend with two or more components achieves the desired quality of a normal commercial flour: the components must suit each other and have a high energy value as well as a sufficiently high ratio.

130 To increase the protein content of a flour and improve its baking properties it is usual to add 2 - 3% vital wheat gluten (dried gluten). Rehydrated wheat glutens have different physical and rheological properties according to the initial quality of the flour, the method of drying the gluten and the temperature at which it was dried during its production at the starch factory. When the glutens are added to the flour, these properties are clearly visible from the viscoelastic properties of the dough and thus ultimately from its baking performance. Even when dried gently, every wheat gluten suffers heat damage which manifests itself in different degrees of reduction of the water-binding capacity and extensibility and in an increase in the elasticity of the rehydrated gluten or in its shortness. The properties of the rehydrated wheat gluten can be tested sensorily, by hand, or by conducting extension and shear tests, but an Extensogram of the flour mixture shows most plainly the effect of the wheat gluten in conjunction with the proteins of the flour (Weipert and Zwingelberg, 1992). A flour with soft, weak dough properties requires a firm wheat gluten that is not very extensible; a flour with short dough properties can be improved with a soft, extensible gluten. It is really very surprising that the usual addition of about 2% wheat gluten has such a decisive influence on the dough properties of the flour.

All in all it may be said that Extensograms make it possible to describe the quality of a flour clearly and with sufficient reliability. They describe the viscosity or consistency of the dough, which can be checked by the water absorption determined in the Farinograph. But what is even more important for processing the flour is that they describe the viscoelastic properties of the dough and make a considerable contribution to the quality of the final baked product.

The rheological properties of the freshly washed out wet gluten – called "gluten structure" by the cereal processors – have long been described by means of stretching by hand in a sensory test. This sensory rating has been made more objective by mechanical, automatic washing and the use of simpler instruments. A measurement of this kind carried out with a Glutograph or texture analyzer or determined as a gluten index can doubtless be taken as a guide. But it cannot completely describe the properties of the dough (Bloksma, 1990, Weipert, 1998a and Weipert and Zwingelberg, 1992). The behaviour of isolated wet gluten and rehydrated dried gluten alone is quite different from their behaviour when they are combined with starch, pentosans, lipids and other ingredients of dough.

In the case of a wheat flour for bread making, the proteins are expected to form a gluten as quickly as possible; the gluten must bind water and thus determine the consistency of the dough. On the other hand a flour for making wafers is expected to form gluten late or preferably not at all, so that the mass retains a low viscosity. The suitability of wafer flours is determined with the aggregation test and the viscosity test using a flow pipette (Gluzynski *et al.*, 2002). Both are ultimately a measurement of the viscosity and viscoelasticity of the mass.

Rheofermentometer and Texture Analyzer

Baked volume and the characteristics of the crumb are the two most important quality attributes of baked products. Both are determined by the choice of raw materials (wheat, flour, yeast, other ingredients, additives etc.) and influenced by technical measures and can be demonstrated for the entire chain of production in the individual phases, starting with the raw material flour, through the dough processes and finally in the crumb as the end product. Since we are dealing with physical properties of the substances it is possible and appropriate to determine the characteristics of the raw materials by rheometric methods and observe the effects of the technical measures and treatments used. Food rheometry offers a number of measuring instruments that differ greatly in respect of their efficiency, the information they provide and not least their acquisition and running costs. The measuring instruments of applied and fundamental rheology most in demand are those that are simple to use, have a good price-to-performance ratio and are suitable for measuring various different materials.

Rheofermentometer

The Rheofermentometer (Tripette et Renaud/ Chopin, Villeneuve la Garenne, France) is an instrument that measures the interaction of gas production and gas retention in wheat doughs from a practical point of view. Maximum CO_2 formation and the moment at which gas is released from the dough during fermentation can be read off from a gas formation curve, and the ratio of the amount of gas retained to the overall amount of gas can be calculated. Corresponding to this, a curve for the height of the dough is recorded; it shows the maximum height and the stability of the dough (before the CO_2 is released), also during fermentation. A simultaneous analysis of the two curves reveals the fermentation properties of a yeast and a dough under given conditions and permits conclusions with regard to the characteristics of the raw materials (various flours, yeasts, sugar) and the measures that have to be taken to optimize the production process. This viewpoint distinguishes the Rheofermentometer from the Brabender Fermentograph and the Maturograph.

The Rheofermentometer has been used throughout the world to investigate the gas retention capacity of different qualities of the raw material flour (flour grinds, wheat varieties, sprout) and their reaction to the addition of dried gluten and ascorbic acid, and also to study the effect of maltose and other sugars (sucrose, lactose) and α-amylase on the development of the gas. Some ingredients such as carboxymethyl cellulose have also been known to cause changes in both gas retention and gas formation capacity. Special attention is given to the effects of the dairy products low-fat and full-cream dried milk, whey and caseinate; being surface-active substances, these have an enormous effect on baked volume. These investigations have helped to optimize the formulations of such products. Tests with the Rheofermentometer have shown that the fall in baked volume caused by the storage of frozen dough portions is caused not by reduced gas retention but solely by reduced gas formation capacity. This has also been taken into account when optimizing formulations (ingredients, speed of freezing).

The Rheofermentometer has therefore shown itself to be a useful instrument in practical baking. To answer specific questions the measuring program suggested by the manufacturer of the equipment can and must be altered.

Maturograph and Oven-Rise Instrument

For some time the gas formation and gas retention capacity of a dough made with yeast has been measured with a combination of two rheometric devices, the Brabender Maturograph and the Oven-Rise Instrument. The Maturograph records the change in volume of a dough fermenting with yeast by tracing the shape of the dough specimen with and without pressure; in this way it determines both the viscoelastic properties of the dough and the time of greatest activity of the yeast or the end point of fermentation. At this time a sample of dough from the same batch is "baked" in oil heated to a controlled temperature, and the oven rise of the yeast is described under conditions similar to those of an oven by recording the amount of rise or the loss in weight of the sample. These two methods form a bridge between the cold phase of the dough in the fermentation chamber and the hot baking phase in the oven in the form of a recording laboratory test without the need for a baker's oven or a direct baking trial.

The two devices can be used successfully and helpfully for practical and scientific purposes in cereal laboratories. They make it possible to examine a number of raw materials (wheat, flour, yeast), to optimize flour blends and methods of flour improvement, to develop, make up and test ready-mixed flours for special products, and ultimately to adjust flour qualities to the existing production process or the production process to existing flour qualities. Inclusion of the Do-Corder, a recording mixer with adjustable mixing intensity, in the measuring procedure with the Maturograph and Oven-Rise Instrument to make up the DMO (Do-Corder-Maturograph-Oven Rise) System has complemented and greatly consolidated the information yielded by the test. The system also describes the behaviour of the dough as a reaction to intensive mechanical stress and recognizes the mixing requirements and kneading tolerance of the dough. The introduction of the DMO System has finally enabled a more complete description of the suitability of flours for various different baking purposes (Seibel and Cromentoyn, 1964; Brabender 1965, Brabender and Schäfer 1971, Schrader 1984).

Texture Analyzer

The Texture Analyzer (Stable Micro Systems, Goldalming, England) is a universal instrument that justifies its popularity in two respects. It works on the principle of a compression and tension measuring device with a range of different tools. Universal instruments of this kind, with the same measuring principle, have existed for a long time. But because of its size and ease of operation, this device is also suitable for cereal laboratories. On the one hand its versatility enables the user to make simple, quick and objective measurements of viscosity with materials of different consistencies and structures such as whipped cream, mustard, ketchup, starch gel and also wet gluten, dough, and the crumb of baked products. It is even possible to measure the fracture strength of crispbread and biscuits. On the other hand, a feature of the universal nature of the instrument is that the free choice of loads makes it possible to describe the flow properties of a substance in the sense of fundamental rheometry.

Being a tensile instrument it is similar to a Mini-Extensograph that can record the structures (viscoelastic properties) of the wet gluten and the dough strands by measuring their extension (using a small sample and the Kieffer rig). This makes it possible to describe both the quality of the wheat or flour as raw materials and the effect of the additives and ingredients on the properties of the dough.
Used in the compression mode the instrument simulates the baker's finger, and by penetrating the specimen (depth of penetration as a function of the force applied and time) it ascertains the viscosity of the dough (and thus its water absorption) (Tscheuschner and Auermann, 1964) and also the crumb characteristics of the finished bread. Compression of a sample of bread crumb defined in terms of geometric dimensions makes it possible to record and describe the texture of the sample even more precisely and reliably – useful for describing the chewiness and staling of the crumb. Similarly, a suitable measuring technique can be used to describe the cooking properties of pasta. Further measuring cells have recently been developed that make it possible to measure the "stickiness" of a surface (dough, bread crumb, pasta, rice) and state it in terms of numbers, or to describe the characteristics of dough by means of biaxial stretching, as for the Alveograph (Dobraszcyk, 2002).

Hot Phase of the Bread-Making Process

Whereas the focus of attention in the cold phase of bread making is on the swelling substances of the flour, particularly the proteins, it is starch and its pasting behaviour that dominate tests to show the behaviour of doughs in the hot phase, i.e. the actual baking. Starch only starts to swell intensively at elevated temperatures; it binds water and gelatinizes, losing its crystalline structure. But the gelatinizing and already gelatinized starch is exposed to enzymatic breakdown through the activity of α-amylase. In the quick breakdown process of the enzymes the starch loses its ability to bind and hold water; this results in bread with an inelastic, soft, wet and very often unchewable crumb which makes the product inedible. On the other hand, optimum enzyme activity is necessary for optimum results in the baked product. So it is essential to determine the activity of the α-amylase in a flour or any other ground product in order to achieve the desired result. If the enzyme activity is too high, activity-inhibiting agents are added or suitable measures taken; if it is too low it can be optimized by adding enzyme preparations.

For practical and technical reasons, the activity of the α-amylase is ascertained indirectly by measuring the viscosity in a flour-and-water slurry. When interpreting the measurements obtained by various methods we have to be aware of the fact that:

- **the observed changes in viscosity are not due solely to the interaction between the starch and the enzyme; they also reflect the water-binding capacity of the swelling substances in the flour, and**
- **although the gelatinization of the starch is a function of the elevated temperature or the heat energy introduced, the concentration of the slurry and the temperature gradient with which the rise in temperature in the slurry is controlled have an enormous effect on the gelatinization process of the starch. So the measurements made with the Amylograph, the Rapid Visco Analyzer and the Falling Number apparatus are not directly comparable.**

Amylograph and Falling Number

The Amylograph is a rotational viscometer with a measuring system consisting of a round vessel, in which the flour-and-water slurry is heated under controlled conditions, and a sensor to record the changes in viscosity during the measuring time. The pins of the measuring device cause turbulences in the slurry; these are necessary to prevent sedimentation of the starch, but they make it impossible to calculate the viscosity precisely in absolute physical units. The viscosity of the slurry is therefore stated as torque in Brabender or Amylogram units. The measurements that can be read off include the temperature and the viscosity at maximum gelatinization; these provide more differentiated information than a viscosity value alone.

The Amylogram, a viscosity curve showing the gelatinization of the starch in the flour-and-water slurry, reflects the changes in water binding capacity of the swelling and pasting starch and the enzymatically and mechanically decomposed starch gel. In the way the standard Amylograph method is used it offers a suitable means of describing the pasting properties of rye flour slurries. Rye starch gelatinizes at lower temperatures than wheat starch, especially if it is sprout-damaged as a result of poor environmental conditions. Then the task is to find out whether the rye is suitable for baking by determining the temperature and viscosity at the pasting peak of the Amylogram. This applies to wheat too, but only if it is assumed to be sprout-damaged. The starch of the flour slurry from a wheat lot that is not sprout-damaged normally gelatinizes later and at higher temperatures, towards the end of the temperature range of an Amylogram or the measurements from an Amylograph. However, a very high viscosity at the pasting peak yields little information in relation to the amount of time that has to be invested. For such wheat flours the quick and simple determination of the Falling Number is sufficient.

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Falling Number determination is a simple and quick method in which the viscosity of a flour-and-water slurry is stated as the number of seconds a pestle takes to penetrate the starch gel. Measurement of the viscosity in a Falling Number tube does not start until 60 seconds after stirring, when the viscous properties of the gelatinized starch slurry have already been changed by the α-amylase present in the flour and the mechanical force of stirring. The Falling Number is therefore a one-point measurement of the residual viscosity of the starch gel, not a continuous measurement like that of the Amylograph. The Falling Number method can be used for both wheat and rye, although the limits of the measurements differ. This results not least from the different water binding capacities of the swelling substances of wheat and rye. In rye flours too, the Falling Number can be used with sufficient accuracy for indirect determination of α-amylase activity and the suitability of a flour for baking.

112 There is not a close enough relationship between the Amylograph and Falling Number methods to permit a direct comparison of the measurements. Firstly, the ratio of flour to water (concentration of the slurry) and the time/temperature gradient of the heating differ; secondly, the Amylograph method is a continuous measurement over a period of up to 45 minutes, whereas in the case of the Falling Number the measurement of residual viscosity does not start until after 60 seconds of stirring. For these reasons it is not possible to allocate an Amylogram value to a corresponding Falling Number. Nevertheless, a numerical relationship between the two methods can be achieved by comparing a large number of measurements and calculating a mathematical-statistical regression. But this relationship only applies to the harvest of a single year and has to be reviewed or re-calculated for each new harvest.

By using nomograms in a double-logarithmic system it is possible to make up optimized mixtures from rye flours with different Falling Number and Amylogram data (Weipert, 1987c). However, the percentages of the enzyme-active components with low data depend on the height of the data of the low-enzyme components; as a rule these percentages tend to be low.

Rapid Visco Analyzer

Whatever the advantages for which the Brabender Amylograph (and the Viscograph, intended chiefly for the starch industry) is appreciated, it has disadvantages too. Firstly it requires a very large sample for testing, and secondly the recording of a pasting curve is time-consuming. Several attempts have recently been made to develop and market a "micro-Amylograph". The development of the Rapid Visco Analyzer (Newport Scientific, Sydney, Australia) was and is still the biggest and most successful step towards simplifying and broadening the investigation and description of the pasting properties of starch and products containing starch (Weipert, 1998a). Because of its versatility it is in general use in the field of food analysis (milk, soups, sauces, salad dressings etc.).

The Rapid Visco Analyzer is also a rotational viscometer that unites the advantage of requiring only a small sample (2-4 g) with the possibility of setting to any desired temperature gradient. The temperature profile of a test can be adjusted in such a way that the test starts at any chosen temperature, which rises slowly or rapidly and remains constant for a time before cooling down in the desired steps. In practice this means that the test can be performed at a constantly high temperature in the manner of the Falling Number test, with slow or faster heating in the manner of an Amylograph or with controlled heating and cooling as in a Viscograph. A close correlation has been found between the measurements from these two methods and the results of the Falling Number and Amylograph tests; this correlation enables the Rapid Visco Analyzer with the already standardized methods ICC "stirring number" (similar to the Falling Number) and "rapid pasting" (similar to the Amylograms and Viscograms) to be adopted by cereal laboratories and used "seamlessly" (Weipert, 1998a). 113

Interpretation of Brabender viscograms and the RVA rapid pasting curves:

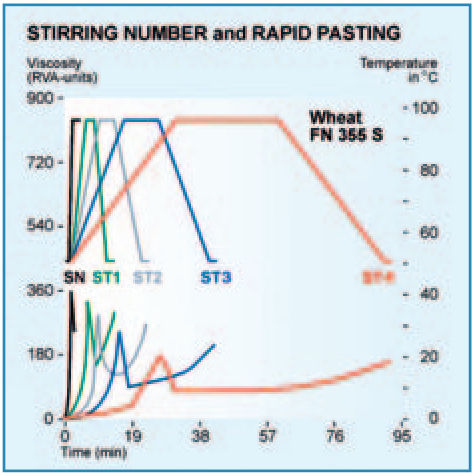

Fig. 60: Temperature ramps (upper set of curves) and pasting curves (lower set of curves) of a wheat flour recorded in the Rapid Visco Analyzer at different temperature gradients:
SN: constant 95 °C; ST1: 12 °C/min;
ST2: 6 °C/min; ST3: 3 °C/min;
ST4: 1.5 °C/min

The possibility of programming and determining the duration of a test for the pasting behaviour of starch in a starch/water or flour/water slurry oneself, according to needs, and thus monitoring the behaviour of the starch in the relevant process is very much appreciated by users of the Rapid Visco Analyzer. A quick method can doubtless yield a reliable result as a guide, but the process of making and baking bread takes rather longer. In order to describe the pasting behaviour of wheat and rye starches in flours for baking and to assess it in the manner of an Amylogram, the measuring time in which the starch swells and gelatinizes must be taken into account. The starch grains have time to absorb and bind the water, to swell, to be "annealed", and finally to gelatinize completely or incompletely, depending on the amount of free water available. One and the same flour/water slurry shows different viscosities and temperatures at the pasting peak according to the length of the measuring time. The shorter the measuring time, the higher the viscosity; it is therefore highest in the "stirring number" method, similar to the Falling Number (Fig. 60). To save time by shortening the measuring period may mean a loss of information (Weipert, 1998a), especially if the quality data from the time-consuming Amylograph method are still used on the grounds of experience. Nevertheless, a "quick test" of this kind may serve as an initial guide. Farther-reaching decisions require the introduction of new critical values for each of the suggested temperature profiles in the course of measurement. The Rapid Visco Analyzer can measure both fast and slowly.

13.1.5 Fundamental Rheometry

Fundamental rheometry came into being with the pioneering work of G. W. Scott Blair – and it is characteristic that the material he used for his trials was a wheat dough (Schofield and Blair, 1932). This substance, that was initially a problem to the rheologists because of its "memory" (meaning the stored energy of its elastic behaviour), subsequently took rheometry and rheology a great step forward.

There is a relationship between conventional and fundamental rheometry. They use a similar deformation force, but in fundamental rheometry this is variable and therefore capable of describing the flow properties of a material under different loads or stresses in a test with a universal viscometer. The result is a flow curve, or stress strain curve, in which changes of stress are recorded over changes in strain. The stress in the curve is either the chosen deformation force, by which the change in strain is measured, or it is a measure of the resistance to deformation if the strain is varied under controlled conditions during the test. In both cases the viscosity is calculated from the two physical values stress and shear rate, and since the magnitude of the deformation force (measured area and force) and of the strain is defined, it is expressed in absolute physical units. These physical units permit a direct comparison of results from viscometers made by different manufacturers. Moreover, by calculating the viscosity, a flow curve can be "redrawn" as a viscosity curve (Fig. 61); the two types of curve yield the same information, and it is up to the person interpreting the results to choose the type of curve he prefers. The two types of curve show the flow properties of the substance tested; in particular they indicate any shear-dependent or time-dependent anomalies of flow behaviour that may occur in the test. The viscosity curve of a dough yields very important information on the rheological properties of the dough under different deformation forces. It shows that the dough has a yield point, and that its viscosity (consistency) falls as the load increases. This property is known as structural viscosity or shear-thinning and is caused and explained by the orientation of the molecules and aggregates in the flow field. It means that when exposed to only a low deformation force, such as stretching by the fermentation processes during the resting time, a dough has a higher viscosity than during transportation through the pipes or testing with the Farinograph or Extensograph (Fig. 61). This justifiably raises the question of how to describe the state of a dough at the low deformation forces in the process with a method that uses high deformation forces (Tanaka, *et al.*, 1980). In other words: with high deformation forces it is only possible to determine the mechanical properties of the dough, not its rheological properties.

A comprehensive work by several authors has been published on the subject of food rheology in general and the advantages of fundamental rheometry, including dough rheology, in particular. It deals with the importance of rheology for explaining and improving the quality of foods (Weipert and Tscheuschner, 1993).

The deformation curve of an Extensogram and the stress strain curve are similar in appearance and take a similar course (Fig. 62). It is hoped that this fact will lead to greater acceptance of fundamental rheometry in cereal laboratories. There is no similarity to the Alveogram, since it is a pressure curve and not a deformation curve. If a ruler is placed behind the expanding dough bubble so that the increase in the size of the dough bubble can be measured, the resulting deformation curve made up of the measured points also shows similarity to the Extensogram.

Viscometer

The instruments used in rheometry differ in respect of their measuring principle, their mode of use and thus the presentation of the results. In rheometry the flow behaviour of a material is monitored between two parallel flat plates, in the circular gap between two

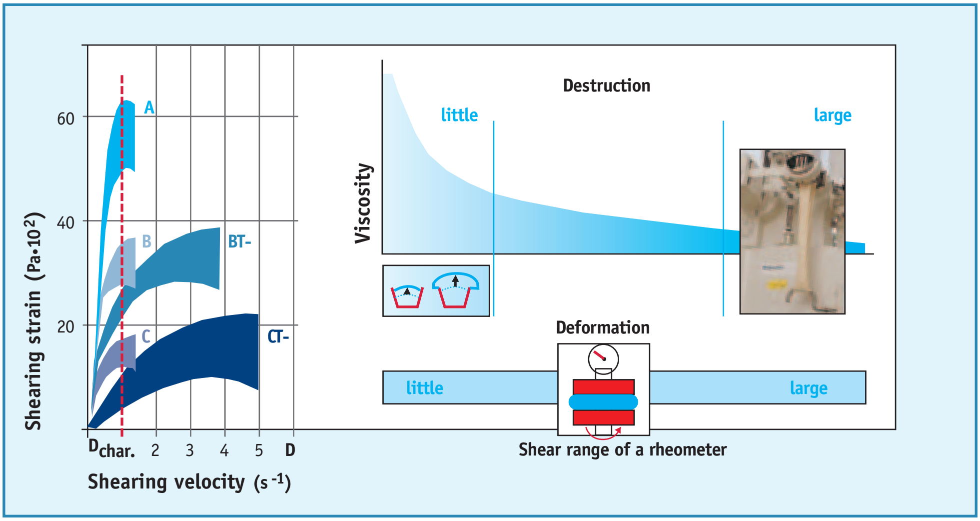

Fig. 61: Stress strain curves of wheat flour doughs with different dough properties recorded with a rotational viscometer (left) and a viscosity curve showing "yield point" and "shear thinning" (right)

coaxial cylinders, between two round parallel plates, between a cone and a plate or finally in a capillary tube. The rotational viscometers have shown themselves to have various advantages and are therefore the most widely used. A rotational viscometer determines the viscosity of a material in a simple test; in the measuring gap of the instrument the conditions are "stationary" and the flow is laminar. A relatively simple and therefore inexpensive viscometer makes it possible to record stress strain curves that reveal certain information about the dough. The yield point and the viscous properties of a dough can be read off from the shape and pattern of a stress strain curve and the (automatically) re-calculated viscosity curve. From the viscosity it is possible to determine the water absorption or the volume yield of the dough. The shape of the stress strain curve reveals the properties of the dough: a dough with short properties has a steep stress strain curve, whereas the curve of a dough with soft, weak properties is flatter (Fig. 61). And finally the stress strain curve makes it possible to assign a numerical value to the surface stickiness of a dough (Weipert, 1987a, 1992, 1998 and 1998b). So it is no wonder that such a method, which requires very little specimen material (10 g flour), is used successfully in the breeding of wheat (Fig. 61).

Rheometer

A rheometer can measure viscosity in the same way, but it can also show the elastic properties of a material in a second test in which the specimen is briefly stressed by sudden shearing at a controlled rate, and the stress then suddenly ceases. As a rule the test only takes a few seconds and produces measurements in the form of a curve. The curve rises sharply in relation to the stress and falls again more or less steeply when the shearing suddenly stops. The falling end of the curve shows the elastic properties of the material; it reveals a reversible elastic deformation and an irreversible plastic deformation (Fig. 63). The measurement is "unsteady" because of the sudden changes in the flow field of the specimen.

A special class of rheometers consists of instruments which enable the rheological properties of a material to be demonstrated in a single test. To do so they operate in the dynamic oscillating or vibratory mode: instead of shearing simply by rotation in one direction they perform an oscillating measuring deformation in which the amplitude of the oscillations (excursion) and their frequency (movements within a unit of time) can be controlled (Fig. 64). Viscosity is measured as torque according to the familiar method and

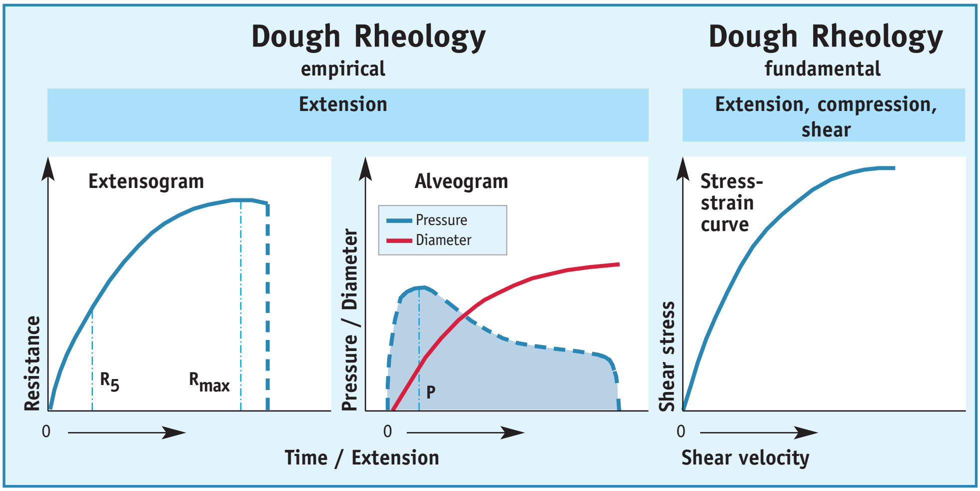

Fig. 62: Comparison of recorded curves: Extensogram, Alveogram and stress-strain curve

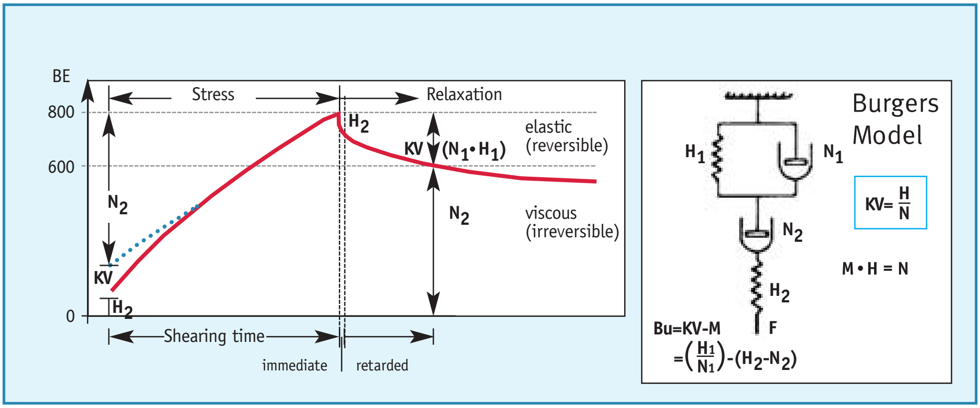

Fig. 63: Creep recovery / stress relaxation curves of a gluten or a dough

shown as complex viscosity, but the "stiffness" of the material is also recorded as stored elastic energy. The result of the measurement is a sinusoid ("wavy") curve. A comparison of the curve thus produced with the controlled deformation curve reveals a phase shift measured in angular units between 0° and 90°. The smaller the phase shift, the "stiffer" and more elastic is the tested material. The "plastic" component of viscosity, the energy loss, cannot be measured; it is calculated as an imaginary component, the difference between complex (total) viscosity and the stored (elastic) viscosity. "Plastic" viscosity divided by elastic viscosity denotes the viscoelastic behaviour of the material tested. For reasons of simplicity the results are usually stated in the form of measured moduli that have to be converted into viscosity values by calculation. The conversion factors for a measurement are constant, so that the moduli G* (complex shear modulus), G' (storage modulus) and G" (loss modulus) stand for the relevant viscosities (complex or total viscosity, elastic viscosity and plastic viscosity). Viscoelasticity is calculated as tan delta (tangent delta or loss angle), the quotient from G" divided by G'. If this is smaller than 1, since G' is greater than G", it describes an elastic material; if it is greater, the material is plastic. The greater the deviation of tan delta from this quotient 1, the more distinctly does the viscoelastic behaviour of the material tend in one direction of viscoelasticity or the other, i.e. elasticity or plasticity.

This highly efficient, sensitive and elegant method of recording and displaying the "true" rheological properties of foods has made a great contribution to understanding the specific characteristics and behaviour of raw materials and foods during processing and ultimately to explaining why consumers like one product and dislike another. The definite advantages of the dynamic oscillating method for studying and identifying structural changes in foods during processing can be documented by DMTA (Dynamic Mechanical Thermal Analysis). If a starch/water slurry is heated as in an Amylograph test and the changes in viscosity, elasticity, plasticity and tan delta are measured, several curves similar to an Amylogram are obtained (Weipert, 1995).

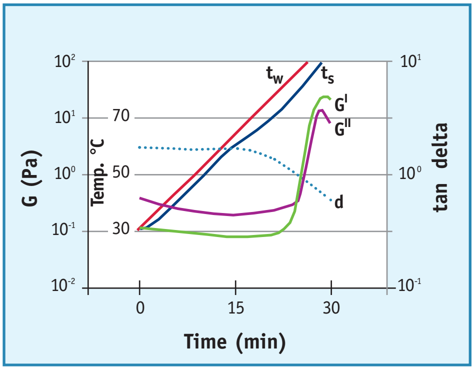

Fig. 64: DMTA of a starch slurry: storage (G') and loss (G") moduli and tan delta over the time in the course of heating (Weipert, 1995)

Dynamic oscillating mode

At the beginning of such a test the loss modulus G" was greater than the storage modulus G', showing that the starch slurry had the properties of a liquid at low temperatures (Fig. 64). At higher temperatures, following increased water absorption and gelatinization of the starch, the situation was reversed: the storage modulus G' was greater than the loss modulus G", indicating that the properties of the starch gel were becoming more solid. These changes were expressed even more clearly by the course of tan delta, which was well above 1 at the beginning of the test and well below 1 after gelatinization of the starch. This means that starch gel has predominately the elastic properties of a "solid". These observations concerning the changes in the viscoelastic properties of the starch slurry were accompanied by measurements of the temperature of the heating medium and of the slurry itself. It was found that the temperature curve of the slurry (T_S) followed the temperature curve of the heating medium (T_W) with some delay, but that a slight rise in the temperature curve of the slurry occurred at the beginning of gelatinization. This additional delay was caused by the fact that the starch took the heat energy out of the slurry in order to gelatinize. In a dough the transformation from a soft, "plastic" mass into a firm crumb in which the "elastic" properties predominate is even more evident. This shows that such a test is useful for identifying and demonstrating the changes in the properties of a flour in the course of processing.

Measurements with such instruments of fundamental rheology have opened up new ways and means of analyzing the structure and properties of doughs. By carrying out a frequency sweep (in which the amplitude remains constant and only the frequency is changed as required) or an amplitude sweep (in which the frequency remains constant and the amplitude varies) it is possible to record the flow properties of a dough at different deformation forces. Both the viscosity and the elasticity or viscoelasticity of the dough are recorded synchronously and simultaneously in a single measurement. This is a simple, quick and elegant way of differentiating between doughs with a firm elastic or soft and plastic structure (Fig. 65). It has also been

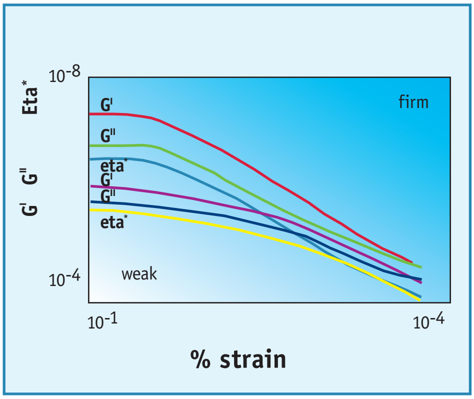

Fig. 65: Deformation (strain) test in the dynamic oscillating mode on wheat flour doughs with extremely different dough properties

observed that at an extremely low deformation load wheat dough shows a plateau of elastic behaviour, since its structure is not damaged during this part of the measurement; the dough does not show the expected structural viscosity as its viscosity decreases under increasing deformation forces. This observation has been used to develop a "non-destructive" testing method, in fact one which scarcely touches the dough, in the form of a "recording baking test" in which the dough is monitored over the desired length of time at rising baking temperatures and falling cooling temperatures under conditions simulating the process in the baker's oven (Weipert, 1987a and 1992). The viscosity and elasticity curves are related to the curve of an Amylogram, since they show the gelatinization properties of the starch in interaction with other flour constituents and additives. But in this case we have a dough of the consistency usual in bread making, and so they show the properties and interaction of these two most important components of a flour and a dough in the baking process. They demonstrate the dough properties resulting from the gluten at the beginning of the process, in the oven stage and as a final result after baking. The measurements after cooling show the properties of the baked dough, which only differs from the crumb of the bread in that the inflation is missing (Fig. 66).

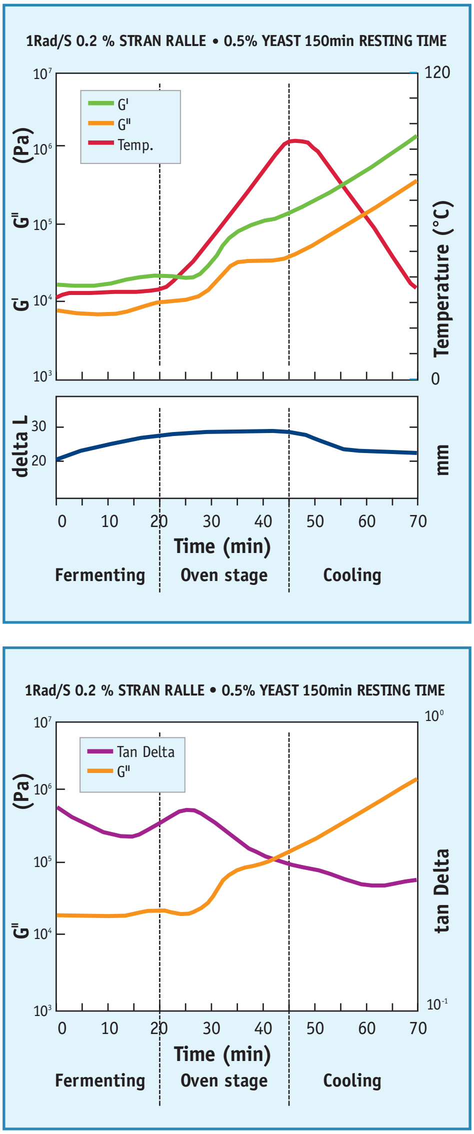

Fig. 66: "Recording baking test" - changes in viscosity (G), elasticity (storage modulus G'), plasticity (loss modulus G"), sample height (delta L) and viscoelasticity (tangent delta) in the course of heating and cooling*

Although still comparatively new, the "recording baking test" method has already shown its value and potential in a few publications. Baking trials using flours from wheat varieties with different dough properties have shown that the viscoelastic properties of the doughs are preserved into the baked crumb. The baked crumb is doubtless firmer and more elastic than the dough, but the crumb of a wheat flour with soft dough properties is softer than that of a wheat flour with firm dough properties. Furthermore, the method showed the effect of the different dough yields, of ascorbic acid, various enzyme preparations, emulsifiers and other ingredients on the viscosity and viscoelastic properties of the dough and the crumb, in respect of extent and also time and temperature (Fig. 67). The influence of the oven temperature was shown with an enzyme-active rye flour by carrying out recording baking tests using slowly and rapidly rising temperature gradients (3.5 °C/min and

7 °C or 17.5 °C/min respectively). It was also possible to simulate the process of producing bread rolls from frozen dough portions. In the measuring device of the rheometer a dough was frozen to -18 °C, heated to +100 °C and cooled down to +30 °C in one cycle during which the changes in viscosity and the viscoelastic properties were recorded continuously. So far the recording baking test is the only method by which doughs can be tested rheologically in their full formulation, including yeast (Weipert, 1987a, 1992, 1995 and 1998b).

But despite the versatility of the rheometer, there are limits to its uses. A rotational rheometer working on the principle of shearing is well able to show the rheological properties of fluids (in coaxial cylinders) and pasty substances (by the plate/cone or plate/plate system), but it fails with solids (Weipert, 1987a, 1992, 1997 and 1998b). On the other hand, a rheometer working in the compression mode might be unable to show the rheological properties of fluids, but its measurement range covers pasty substances (such as dough) and solids of different consistencies (bread crumb, cereal grains) (Weipert, 1997). In the compression mode the measured moduli are termed E* for the complex modulus, E' for the stored modulus and E" for the loss modulus. Both dynamic oscillating measuring principles, the shearing mode and the compression mode, are equally suitable for expressing the rheological properties of materials, complex viscosity and elasticity or viscoelasticity. But since they measure the rheological properties of the specimens in a highly sensitive and precise manner and represent them simultaneously and synchronously, they require friction-free suspension of their working parts in air bearings and complex computer software for control and evaluation. This makes them expensive to buy, maintain and operate (Weipert, 1993). But the new information acquired through the measurements justifies their use.

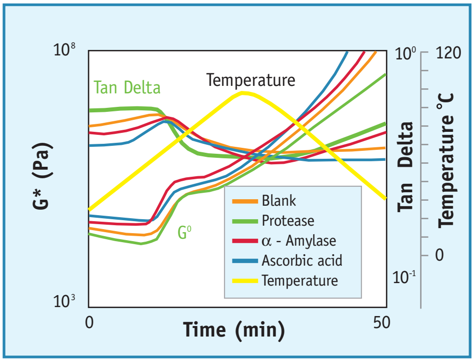

Fig. 67: "Recording baking test" – viscosity (G) and viscoelasticity (tangent delta) of doughs from one wheat flour treated with ascorbic acid, α-amylase and protease*

Simultaneous and synchronous measurement and evaluation

Evaluation programs and computer

13.1.6 Outlook for the Future

Whether conventional or fundamental, rheometry will remain an established and important feature of the production of quality bread and other baked products. The choice of measuring instruments and methods will depend on the level and purpose for which they are to be used. Both rheometries, the conventional and the fundamental, have advantages and disadvantages; an ideal rheometry would combine the advantages of both. But ultimately it is the task of man – the cereal expert and the rheologist – to use the instruments and interpret the results. He has to ensure that Finagle's Law does not apply, namely that:

The information we have
    is not the information we want.
The information we want
    is not the information we need.
And the information we need
    is not available.

The viscosity and viscoelastic behaviour of doughs and the end products is and will always be the information we have and the information we need. And since it is available it offers a guarantee of reliable production processes and good quality in the end products.

13.1.7 Acknowledgments

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