2

Impact of Drying on the Mechanical Properties and Crack Formation in Rice

Catherine Bonazzi and Francis Courtois

2.1

Introduction

According to the IRRI (International Rice Research Institute), more than half of the world's population is dependent on rice.[1] In developed countries, rice is also a major food ingredient for home cooking, industrial food companies, and institutional foodservices. After harvesting, and prior to cooking, rice grains are submitted to several transformations: sieving, husking, milling, and drying, to name the most important in no specific order. Parboiling is an additional kind of unit operation whose main expected benefits are improved nutritional quality and reduced cooking time. Parboiled rice is mostly consumed in South Asian nations. However, it has gained popularity as a part of the cereal diet in recent years in western countries due to its non-sticky cooking and its nutritional qualities (Saif *et al.*, 2004; Sareepuang *et al.*, 2008). Parboiled rice is obtained by subjecting the paddy kernels to soaking and steaming prior to being dried and milled.

Drying is acknowledged to be one of the most important processes when storage time, energy and quality are considered. First, in many countries, rice is harvested at too high a moisture content for safe storage, and hence needs drying for stabilization. The rice grain (also called "rough rice" or "paddy") is usually harvested at a moisture content of about 24–26% (wet basis), higher during the rainy season and lower during the dry season, depending on the region. At high moisture contents, paddy has a high respiration rate and is very susceptible to attacks by micro-organisms, insects, and pests. Heat produced by respiration is retained in the grain due to the insulating effect of the rice hull (husk) and the temperature increase results in increased quantitative loss and qualitative deterioration. Grains become rancid, moldy, yellowish, and pest infested. Newly harvested grain with high moisture content must, therefore, be dried to about 14% for safe storage and milling. The drying step can be carried out at ambient conditions or in forced circulation dryers. Only artificial drying can provide the capacity and high drying rates necessary for handling large volumes of paddy, by exposing the paddy to high temperatures for a short period of time. Such

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[1] http://beta.irri.org/index.php/Home/Welcome/Frontpage.html (October, 26th 2009).

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drying conditions allow high throughput, but they also enhance the risk of breakage of the kernels. After drying, the rice is hardly ever processed directly; it is stored for a shorter or longer period. From research it appears that the storage conditions are also important for the quality of the product, especially for the percentage of unbroken kernels (Kunze, 1979). But even if the kernels are not broken within the dryer, they may have been mechanically stressed, generating fissures or cracks that will be "revealed" by milling and further handling devices.

Rough rice grains, as obtained after harvesting from the field, have a structure as shown in Fig. 2.1. To make the rice suitable for consumption, the hull must be removed. The resulting product is called brown (or "cargo") rice. Various types of equipment are used for the dehulling process, based on friction by rubber rollers or millstones. After dehulling, the rice is often treated further, leaving only the starchy endosperm (see Fig. 2.1). The embryo is also removed. The resulting product is white (or "milled") rice, which contains more starch than brown rice, but the vitamin and protein content is much lower (Marshall and Wadsworth, 1994). The fraction removed during the milling of brown rice is called rice bran, which can be sold separately as rice bran oil.

Many experimental results (Aguerre *et al.*, 1986; Bonazzi *et al.*, 1997) have shown the relationship between the drying conditions and the percentage of broken kernels measured after milling, which takes place after the drying step. Drying, and also harvesting and storage, induce cracks in the grains, leading to breakage during milling. Contrary to other cereals, rice is preferably consumed as whole grains. An important quality criterion for the rice industry is, therefore, the percentage of whole, unbroken rice kernels (head rice). The market value of rice depends strongly on the percentage of unbroken kernels, which are roughly worth twice as much as broken kernels (Siebenmorgen, 1994). In occidental countries, broken rice will end up as an ingredient for animal feed.

Conversely, thin cracks could be beneficial when considering the cooking time, since they may allow faster heating due to additional penetration of water within the kernels. Recent (unpublished) studies have shown that this benefit is difficult to

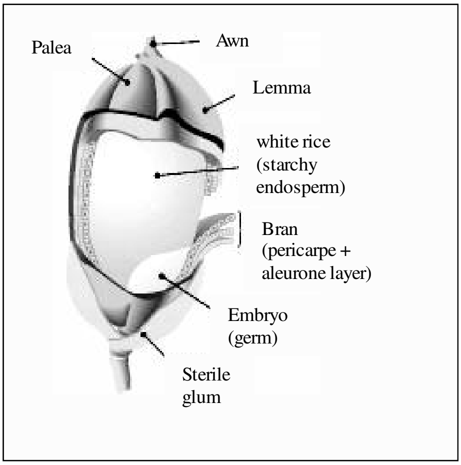

Fig. 2.1 Schematic structure of a rice kernel (hull = glum + lemma + palea + awn).

Tab. 2.1 Possible states for a given rice kernel (and related terminology).

	Non-Fissured	**Fissured**[a]
Length >75% reference length	Intact	Fissured
Length <75% reference length	Broken	Broken fissured

[a] Fissures can be superficial or transverse.

demonstrate through statistics. As a matter of fact, even if some improvement could be proven, its actual effect was less than 2 min decrease over 20 min cooking time.

Cracks and kernel integrity are not the only criteria used for describing rice quality, because color, glass transition temperature, and so on are even easier to measure with instruments. Sensory characteristics, such as smell, taste, texture, are less easy to evaluate. In this chapter, only the main criteria, accessible by means of repeatable instrumental measurements, are detailed, namely the mechanical properties. The effect of drying on both paddy and parboiled paddy rice is discussed.

It should be noted that most studies on rice drying refer to a narrow range of drying conditions, similar to what is actually found in industrial or artisanal dryers. In other words, no study is available on the effect of higher temperature and longer duration drying. This may explain why it is common to observe an insignificant influence of drying on some quality criteria as opposed to the effects of genetic selection or cultural methods that may be much stronger.

The criterion used in industry for evaluating the quality of paddy rice is the head rice yield (HRY, in %) after milling. The rice is processed in a pilot rice-mill, generally consisting of a husker with rubber disks and a mill with an abrasive cone. Husked kernels are then separated into two fractions: a whole fraction and a broken one, using a grain sorter. A kernel is considered broken if its length is smaller than 3/4 of a whole kernel. The result is expressed in terms of rice processing yield, which is the ratio of the weight of white (milled) kernels to the total weight, and in terms of head rice yield, which is the ratio of the weight of whole kernels to the total weight of white rice (ISO norm 6646, see ISO (2000)). This criterion does not take into account whether the kernels are fissured or not (Tab. 2.1).

The different types of fissured/non-fissured and broken/non-broken white rice grains that can be obtained after milling are illustrated in Fig. 2.2.

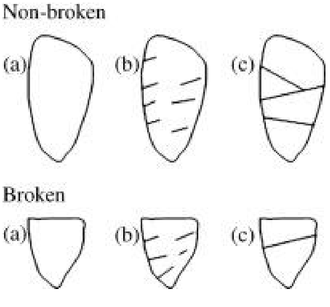

Fig. 2.2 Six possible states for a broken or non-broken rice kernel (a) non-fissured, (b) superficially fissured, (c) deeply fissured. Note that types (b) and (c) can be combined.

There is no reference method to count or characterize fissures in grains. The best (or least-bad) method consists in counting grains with noticeable traversing fissures, which is rather an art than a rigorous technique. As a matter of fact, the method of illumination of the grain is highly responsible for the visibility (or not) of the fissures.

2.2
Impact of Drying Conditions on Head Rice Yield for Paddy and Parboiled Rice

Many authors have described the underlying mechanisms responsible for the creation of fissures in rice kernels. During drying processes the occurrence of moisture and/or temperature gradients cannot be avoided. Because in shrinking systems the volume of the material is dependent on the moisture content (Fig. 2.3) and the temperature, drying will often induce stresses. If internal stress, caused by intra-kernel moisture gradients, exceeds the failure strength of the material, this will lead to cracks or breakage, and, therefore, loss of quality and economic value (Kunze and Choudhury, 1972). If, as is often the case, failure strength is lower in tension than in compression (Akiyama and Kayakawa, 1994), cracks will appear in the zones of tensile stress, and not necessarily at the surface.

Rice is a hygroscopic kernel that gains or loses moisture as the relative humidity (RH) of the surrounding air changes. It was recognized in the 1920s that breakage of rice can be related to rapid drying in the sun, leading to the term “sun-cracks”. Later, it was found that fissures occur during absorption of water by grains of low moisture content. Kunze and Hall (1965) studied the influence of RH changes on the response time before fissuring occurs. An increase in the change in RH corresponds to a

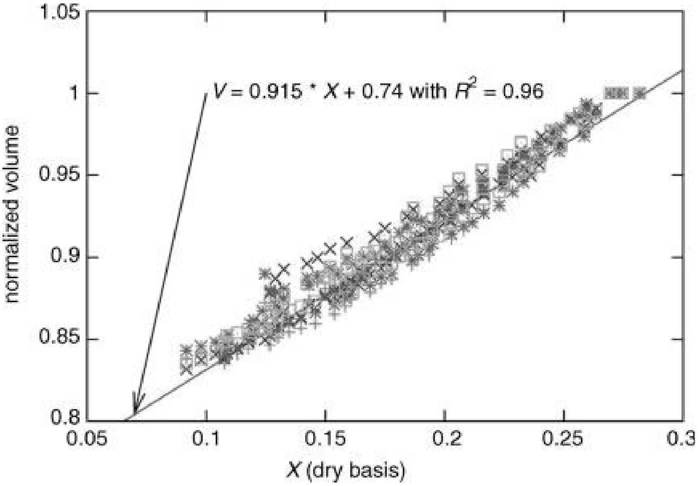

Fig. 2.3 Variation in the normalized volume of cargo rice kernels during convective drying at 40–70 °C. Data from Abud-Archila *et al.* (1999).

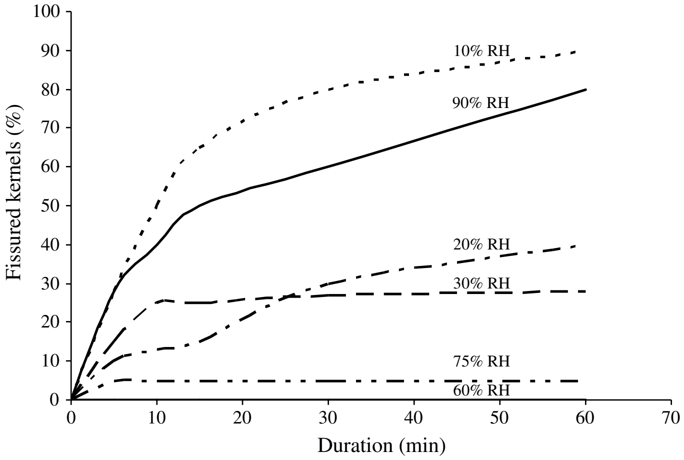

Fig. 2.4 Effect of relative humidity on the fissuring rate of milled Bengal rice (12%, wet basis) at 20 °C. Data from Siebenmorgen *et al.* (2007).

decrease in the time after which fissuring occurs. The response time appears to be inversely proportional to the extent of change in RH, and depends on the rice cultivar. Jindal and Siebenmorgen (1994) and Siebenmorgen *et al.* (2007) showed that thick-kernel cultivars were more susceptible to moisture absorption damage than thinner-kernel ones. The same authors also showed that most fissuring occurred at low (10%) and high (90%) RH, the fissuring rate increasing with temperature (Fig. 2.4).

These results indicate that the magnitude of intra-grain moisture content gradient resulting from absorption or desorption with the surrounding air is important. The effect of the temperature gradient appears much less significant. Kunze and Hall (1965, 1967) observed that heating rice did not cause cracking as long as the equilibrium vapor pressure was kept constant.

Fissured grains are likely to break during milling. The fissures nearly always occur perpendicular to the long axis of the rice grain, and start from the center (Kunze, 1979). The fissures caused by moisture desorption appear to be irregular surface cracks, though regular cracks in the axial direction can also be found (Stermer, 1968). The cracks caused by moisture absorption are internal cracks, perpendicular to the axial direction. The mechanism proposed by Kunze and Choudhury (1972) is that during moisture absorption the outer shell of the grain expands, leading to a compression force at the surface. Because the volume of the cells in the inner parts of the rice grain remains the same or decreases, this will lead to a compressive stress at the surface. Due to the force balance, this implies a tensile stress at the center. If the tensile stress exceeds the failure stress, this will induce fissuring. During moisture desorption the outer shell of the grain contracts, which may lead to surface cracks. This phenomenon depends on the evaporation rate during drying: a higher evaporation rate leads to a larger moisture gradient, causing a larger tensile stress at the center during equilibration. Low moisture grains (below 15 or 16%, w.b. (wet basis)) are more sensitive to fissuring, because they absorb moisture faster than high moisture grains. Further, the deformation at failure is lower at low moisture contents (Chattopadhyay and Hamann, 1994). There is a linear relationship between the expansion of the material and the quantity of absorbed moisture. Therefore, low moisture grains will fissure at a smaller quantity of absorbed moisture. Combined with the higher absorption rate, this explains the sensitivity of low moisture grains to fissuring.

Fissuring due to relative humidity changes can occur before harvesting, during drying or during storage after drying. During ripening of the rice in the field, the moisture content of the grains becomes less dependent on the plant and more dependent on the weather conditions. During a warm, dry day the grain may lose up to 5% moisture (Kunze and Prasad, 1978); in the evening, when the temperature drops, there is normally a rise in the relative humidity. Big changes in the relative humidity occur when hot and dry weather is followed by rain storms, which may lead to fissuring of the grains. Siebenmorgen *et al.* (1992) found that fissuring occurs when the moisture content of the grains reduces to 15% before rain. Usually, there is a large variation between the moisture contents of freshly harvested rice grains. Differences of 10% (w.b.) between grains of the same plant are not uncommon (Kunze and Prasad, 1978). It seems that half of the fissure appears during or before harvest (Sharma and Kunze, 1982), and that the optimal moisture content for harvesting is between 25 and 32% (d.b. (dry basis)) (Chau and Kunze, 1982).

To simulate the storage of freshly harvested rice, Kunze and Prasad (1978) mixed two equilibrated rice fractions with different moisture contents, followed by 48 h storage in a sealed container. It appeared that fissuring occurred in the grains with the lowest moisture content, showing that freshly harvested rice can fissure when stored in a combine hopper, truck, or holding bin. It also appeared that rough (paddy) rice grains have the lowest tendency to fissure, and milled (white) rice grains the highest. Milled rice absorbs moisture about twice as fast as brown rice (Kunze and Choudhury, 1972). The presence of the bran protects the brown rice kernel against rapid humidity changes. In the case of rough (paddy) rice, the presence of the hull leads to an additional protection.

Many researchers have shown that the drying conditions have an influence on the percentage of fissured kernels after drying (Kunze, 1979; Aguerre *et al.*, 1986; Bonazzi *et al.*, 1997; Abud-Archila, 2000). It has also been demonstrated that the percentage of fissured kernels increases with increasing temperature and decreasing relative humidity, and that rapid drying can be very detrimental to rice quality (Aguerre *et al.*, 1986; Bonazzi *et al.*, 1997; Cnossen *et al.*, 2003; Elbert *et al.*, 2001; Imoudu and Olufayo, 2000). A higher evaporation rate, either caused by a high temperature or a low relative humidity, leads to unequal differential shrinkage of the endosperm which results from uneven dehydration of the kernel; rice cracking is then the result of complex stresses caused by moisture gradients in the grain.

Bonazzi *et al.* (1997) demonstrated that the temperature alone cannot explain the formation of cracks and the reduction in HRY observed after drying. As shown in Fig. 2.5, one hour of thermal treatment leads to far different results if drying can or cannot occur (paddy kernels in sealed bags immersed in a bain-marie vs. drying at the same temperatures).

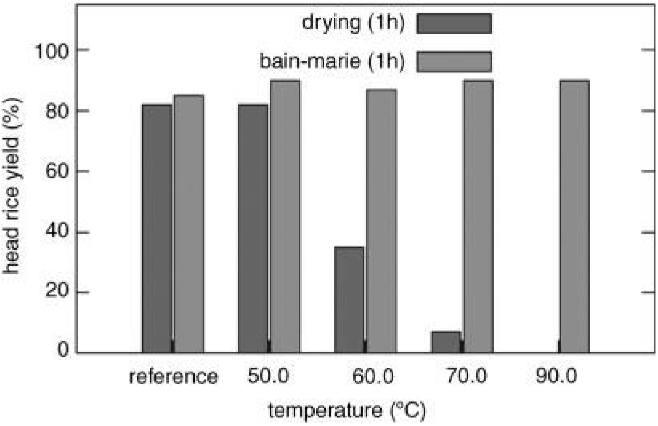

Fig. 2.5 Comparison of pure thermal treatment and drying of paddy rice for 1 h at similar temperature setpoints. Drying is done with a static bed air dryer while thermal treatment is obtained by immersing in a sealed plastic bag in a water bath ("bain-marie"). Data from Bonazzi *et al.* (1997).

A reduction in the RH of the drying air at constant temperature significantly increases the proportion of broken kernels after milling (Aguerre *et al.*, 1986; Abud-Archila *et al.*, 2000). On the other hand, an increase in RH can allow high temperatures to be used without any loss of kernel quality (du Peuty *et al.*, 1994; Bonazzi *et al.*, 1997).

Furthermore, most fissures do not occur during drying, but within a period of 48 h after drying, due to the equilibration of the moisture content within the kernels. This phenomenon was underlined by Kunze (1979) for drying temperatures ≤60 °C and confirmed by Sarker *et al.* (1996). However, kernels can also be fissured during the drying step if more drastic temperatures and/or air evaporating capacities are applied (Fig. 2.6), provided that the internal stresses due to high moisture content gradients exceed the failure strength (Abud-Archila, 2000).

Some authors call for a tempering time between two periods of drying in order to reduce internal stresses (Yang *et al.*, 2005; Schluterman and Siebenmorgen, 2007). The longer the rest, the more significant is the HRY improvement (Thakur and

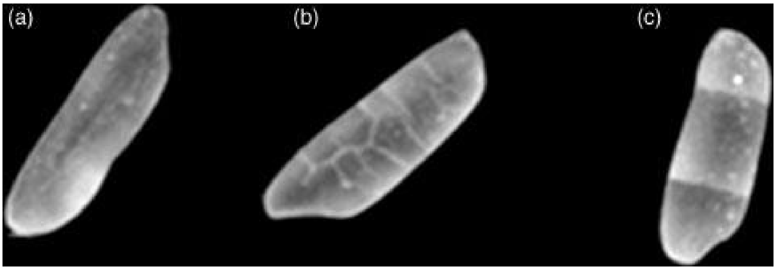

Fig. 2.6 Examples of (a) non-broken and non-fissured, (b) superficially fissured, and (c) deeply fissured kernels. Pictures from a flatbed scanner; contrast has been artificially augmented for improved visibility.

Gupta, 2006). The moisture content at harvest is also an essential parameter of process design. Iguaz *et al.* (2006) recommended that the reduction in water content should not exceed 3% in each drying step. Aquerreta *et al.* (2007) demonstrated that tempering at high temperature (60 °C) can reduce the percentage of fissured kernels and enhance the HRY, independently of the number of drying steps.

Parboiling can also be used to increase the HRY. Gelatinization of starch that occurs during steaming leads to a better cohesion of grain constituents, making them more resistant and increasing the HRY at milling (Houston, 1972; Imoudu and Olufayo, 2000; Rajkumar *et al.*, 2004; Soponronnarit *et al.*, 2006). The impact of parboiling depends on the quantity of water available in the grain and on the processing temperature (Houston, 1972; Pillaiyar *et al.*, 1994; Bello *et al.*, 2006).

2.3
Characterization of Fissures Formation by Image Analysis Techniques

This section focuses on the problem of estimating the amount of broken kernels and crack-free kernels by means of image analysis. With constantly decreasing prices for computers and scanners or digital cameras, it is more and more tempting to obtain such information with the help of sophisticated software and cheap hardware, allowing broad use all over the world. Many authors have been dealing with image analysis techniques to quantify quality parameters of rice or other cereals. Historically, in the 1970s, visual examination (Srinivas and Desikachar, 1973; Srinivas, 1975) was used. Later, starting from the late 1980s, a CCD camera coupled with a personal computer was preferred (Gunasekaran *et al.*, 1987), ending with the combination of a standard flatbed scanner with an ordinary PC and appropriate software (Cnossen *et al.*, 2003). Hendriks and van Vliet (2001) proposed a solution in which grains can be disposed directly onto the glass surface of the scanner without any manual arrangement, as opposed to previous studies where grains had to be disposed separately in order to avoid touching and facilitate lateral lighting. Unfortunately, the methodology used in this work is incompatible with the detection and counting of stress cracks, since touching grains were not separated by the image analysis algorithm.

Most optical studies are limited to measuring kernel dimensions (length, width, surface area, and perimeter). Consequently, they estimate the head rice yield by considering as broken those kernels whose size is lower than a certain threshold. The HRY should be a mass-to-mass ratio, while images only give pixel-based units. Two methods can therefore be used: either finding a correlation between geometry and HRY, or estimating the 3D volume of each kernel from its 2D characteristics. Both methods are arguable: the former requires lengthy calibration, while the latter assumes some symmetry around the kernel long axis.

Few studies deal with crack measurements, mostly by detecting which kernels are fissured and which are not. Only one of the surveyed investigations (Abud-Archila *et al.*, 1999; Abud-Archila, 2000) has treated extensively the position, type, and moment of appearance of fissures on kernels during drying and the subsequent tempering time. This work relied strongly on the careful manual positioning of only

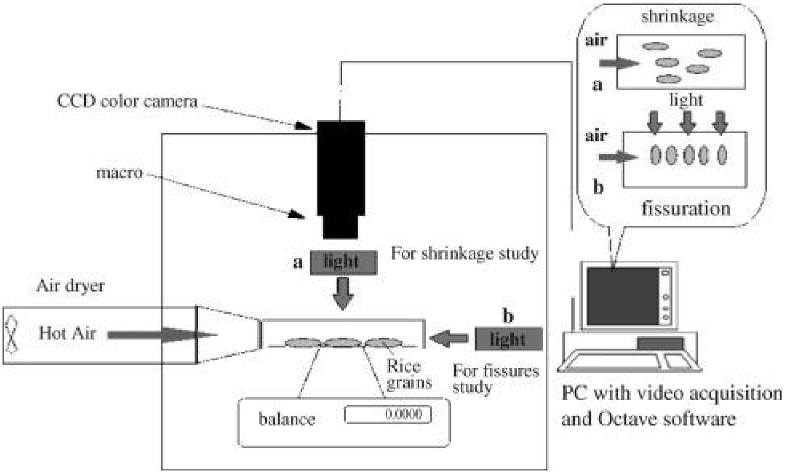

Fig. 2.7 Scheme of video acquisition of shrinkage and cracking of rice kernels during drying according to Abud-Archila *et al.* (1999).

10 cargo (dehulled) grains on a corrugated cardboard with lateral illumination (see Fig. 2.7). Since the grains were manually picked up as non-broken, the measurement focused on the appearance of stress cracks that would diffract the lateral illumination. The calculation method was global: On the basis of the grayscale distribution histogram, the authors noticed that a normal non-broken kernel was associated with 2 peaks (one for the germ and one for the rest) while a fissured one would give $2 + n$ peaks (for n fissures) (Fig. 2.8). According to their observations, the standard deviation on the grayscale histogram was considered as the best estimate for the appearance of stress cracks in the kernels. Two different types of analysis were conducted during drying, in respect to (i) the apparition of fissures (using lateral illumination), and (ii) the shrinkage of the kernels (using frontal illumination). The

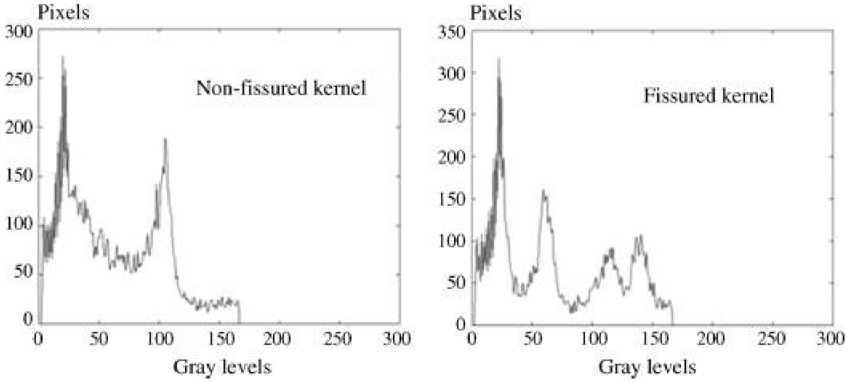

Fig. 2.8 Comparison of gray level histograms of non-fissured and fissured grains. Fissured grains are obtained after drying at 60 °C and 3 h cooling at ambient temperature. Data from Abud-Archila *et al.* (1999).

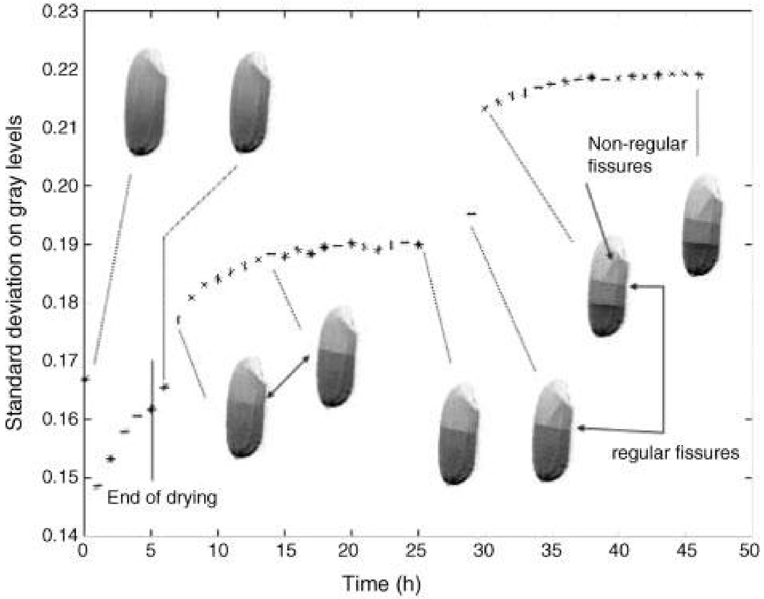

Fig. 2.9 Kinetics of gray level standard deviation during drying and subsequent cooling at 50 °C. Data from Abud-Archila *et al.* (1999).

purpose was to correlate the appearance of cracks with the shrinkage, as it is widely admitted in the literature (see for instance Kunze and Choudhury, 1972). The experiments were carried out in a lab-scale dryer with a sample chamber made of glass to allow for camera filming and different lighting angles (see Fig 2.7). Experiments were focused on drying, with a subsequent cooling period, and the appearance of cracks was recorded during drying and cooling (Fig. 2.9). This method enabled one to distinguish superficial cracks from deeper ones, but had several drawbacks:

- It is incompatible with random placement of grains, limiting its use for large samples and the statistical significance of the studies;
- The lateral illumination tends to reveal mostly perpendicular cracks, biasing the results.

In order to compensate for these disadvantages, Courtois *et al.* (2010) proposed a method using a standard flatbed scanner and a PC with open source software IMAGEJ [2] for accessing both HRY and stress cracks on randomly disposed grains. In such a configuration, many grains are touching, making the segmentation procedure (i.e., the ability to distinguish between individual kernels) highly problematic. Hence, a new algorithm based on an efficient segmentation method has been developed in Java using the IMAGEJ library of routines (Faessel and Courtois, 2009). This segmentation technique relies on a gap-filling method, where the skeleton of the background image is introduced to draw clipping lines between touching grains. An implemen-

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[2] Open source image analysis software written in Java. Free download at http://rsbweb.nih.gov/ij/.

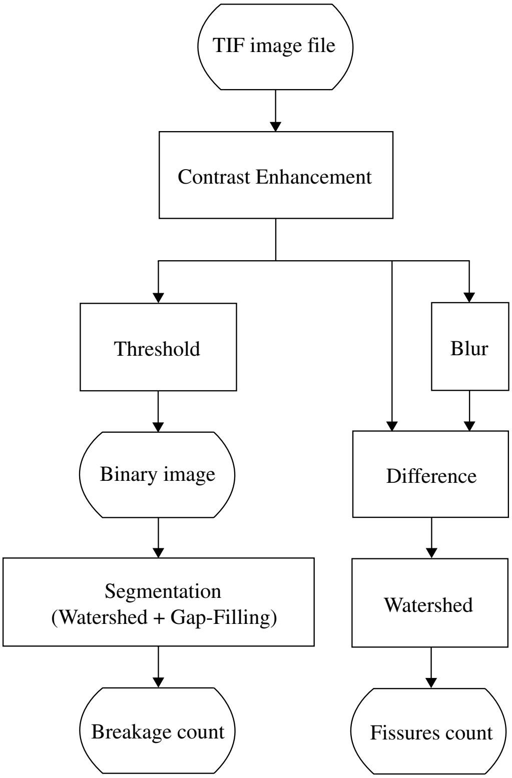

Fig. 2.10 Main steps of the breakage and fissure count algorithm from Courtois *et al.* (2010).

tation of this algorithm was used in order to fulfill the separation process (Fig. 2.10). For images composed of many touching kernels with elliptic shapes, the "gap-filling" algorithm was able to improve the segmentation process.

The mentioned algorithm distinguishes *hard-fissured grains* (having three or more fissures) from *soft-fissured ones* (having one or two fissures). Processing time at 300 dpi ranges from 20 s (segmentation + HRY estimate) up to 1 min (segmentation + HRY estimate + fissures estimate) depending on the number of grains, especially touching grains. Each processed image leads to several results:

- Segmentation ratio (in %): amount of white pixels considered to belong to a kernel versus the total count of white pixels.
- Number of grains or particles detected.
- For each grain, several geometric features are estimated: perimeter, Feret diameter, major and minor (fitting to an ellipsoid), surface area. For fissured grains: number of subparts separated by cracks (unity in case of non-fissured grains).
- For non-broken kernels: mean length and standard deviation of grain long axis (majors), mean specific surface area (surface area to volume ratio), assuming that the grain image is a 2D projection of a prolate spheroid. This parameter is necessary for heat and mass transfer models.

- Number of non-broken and non-fissured grains, broken grains, non-broken and soft-fissured grains, non-broken and hard-fissured grains, both as a count and as a surface area ratio (in %) relative to the total surface area of white grains. Soft-fissured grains are defined as those that have no more than three subparts (i.e., two traversing fissures). On the contrary, hard-fissured grains have more than two fissures.

The software finally produces, for each processed image, one text file containing calculated results and one color image file combining the original grayscale image with color contours according to the following convention: blue for non-fissured and non-broken kernels, green for broken kernels, and yellow or red for soft- or hard-fissured grains.

Using many different samples of parboiled rice, dried in the form of paddy or processed kernels under different conditions, it was possible to cover a wide range of percentages of broken kernels. It is remarkable that the estimates from the image analysis software matched very well measurements using both the ISO norm for HRY and the visual counting (Fig. 2.11).

Since no benchmark method exists for the measurement of the cracks in grains, comparison was made between the total of estimated soft- and hard-fissured grains (in %, relative to the total number of kernels), and a visual inspection with counting of fissured kernels. Since such a visual inspection is tedious, the number of grains was limited to 10–20 whole handpicked grains from samples of different drying histories. To account for this limitation, both estimates were combined with an approximate domain of confidence derived from the calculation of the impact of one-grain error. In other words, the bars displayed in Fig. 2.12 represent the error on the estimate if one

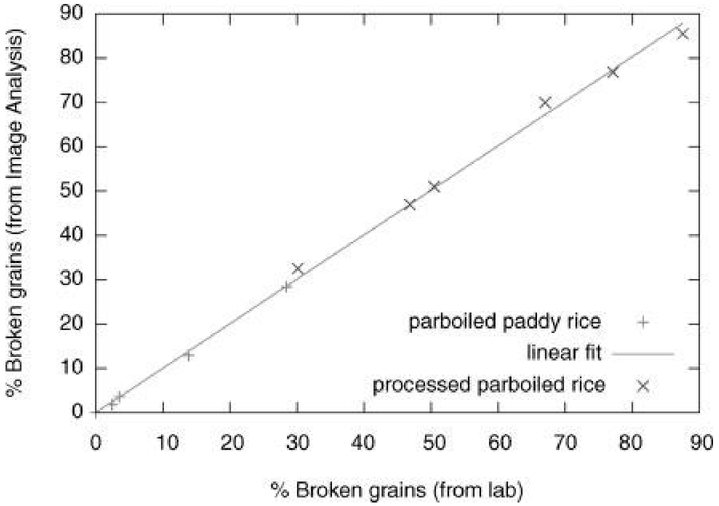

Fig. 2.11 Comparison of breakage ratios obtained in the laboratory by visual inspection or ISO norm analysis with breakage ratios obtained by image analysis. The fitted slope of the line is 1.004 0.009. Data from Courtois *et al.* (2010).

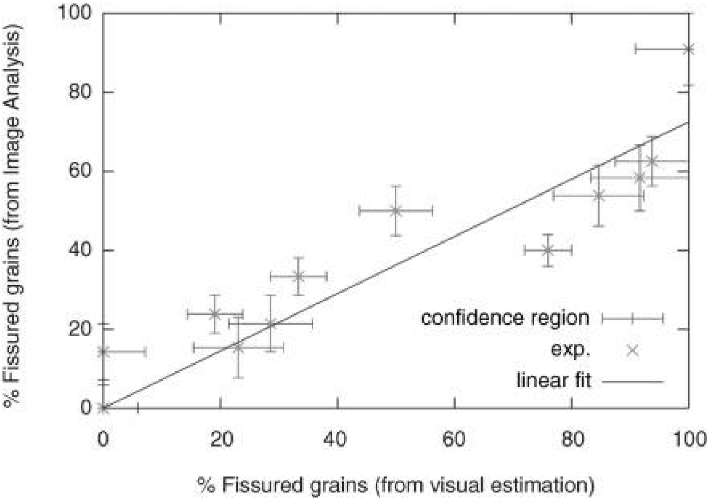

Fig. 2.12 Comparison between fissure ratios as obtained from laboratory visual inspection and image analysis estimation. The fitted slope of the line is 0.72 ± 0.05. Data from Courtois *et al.* (2010).

grain had wrongly been considered as fissured or non-fissured. The match is far less good than in the case of broken kernels, but it can be considered as a first examination tool to check how "damaged" a rice sample is.

There is a potential for new explanations about the formation and propagation of fissures and, hence, breakage by combining both methods: (i) manual positioning of a few kernels, with lateral illumination and a digital camera, and (ii) random positioning of a large number of kernels on a flatbed scanner and advanced image analysis techniques.

It should be noted that both methods present similar problems due to the direction of the illumination. Even on a flatbed scanner glass, the light is moving in a particular direction, emphasizing essentially the perpendicular features. The advantage of studying a large number of grains is purely statistical, but it does not cancel the problem. Ideally, the kernels should be put down on a rotating glass that could allow at least two images with different illumination angles to be acquired.

Using image analysis for estimating the breakage ratio (or HRY) is definitely proven to be reliable. In the mid-term future, a more reliable technique should also be validated for the determination of fissures.

2.4
Characterization of the Mechanical Properties of the Rice Material

As aforesaid, breakage of rice grains during milling can be attributed to the presence of fissures, caused by stresses related to shrinkage during drying. These fissures are usually caused by a tensile failure in the grain. The evaluation of the magnitude of the local strains and stresses, and the determination of fissure initiation and propagation rest upon the constitutive relationship between stress and strain which depends on the mechanical behavior of the materials in the kernel. Very few data on the tensile strength of rice material have been published, which is related to experimental difficulties. Nguyen and Kunze (1984) and Kamst *et al.* (1999) proposed methods that can be used to measure the tensile properties, namely a three-point bending test and a diametral compression test, respectively; (to be described in Section 2.4.2).

Many authors have studied the influence of glass transition on the macroscopic mechanical properties of products (Willis *et al.*, 1999). The viscoelastic properties of materials are modified when crossing the glass transition temperature (T_g): above T_g, water acts as a plasticizer, and the material can distort without developing high stresses. On the contrary, the stiffness of the material strongly increases in the vitrous state ($T < T_g$), and its deformation is accompanied by high stresses which can lead to rupture. Yang *et al.* (2005) explained rice breakage behavior during the drying process by comparing the maximum tensile stresses predicted by finite element analysis with the fracture energy of kernels measured with a three-point bending test at different glass transition states. They showed that the internal tensile stress can only be relaxed or eliminated by tempering at a temperature above the glass transition temperature of the rice. Otherwise stresses will initiate or propagate internal fissures when the kernel goes through the rubbery-to-glassy state transition. This phenomenon helps also to explain why many kernels can fissure some time after the end of drying, during the cooling. Thermomechanical properties of rice kernels were also investigated using a dynamic mechanical analyzer (DMA) by Jia *et al.* (2009). The results showed that the thermomechanical properties were not significantly affected by the cultivar.

2.4.1
Stress–Strain Relationships for Linear Materials

To be able to calculate the stresses occurring during drying, the following information must be provided:

- the relationship between (drying) stresses (σ, defined as the force divided by the contact area) and deformations, or strain (γ, defined as the relative change in the length of the material);
- the relationship between the bulk deformation and moisture content, and also between deformation and temperature if the material is not isothermal.

In most cases the material cannot be regarded as one-dimensional, and forces and deformations in all three principal directions must be taken into account. The normal and shear stresses are interrelated by the equations of mechanical equilibrium. The relationship between stresses and deformations can be described by the generalized Hooke's law in the case of linear elastic behavior. The stress–strain relationship of materials showing more complicated behavior can often be described by advanced theories based on the generalized Hooke's law. All models contain constants that must be determined experimentally, on materials equilibrated in moisture content and temperature.

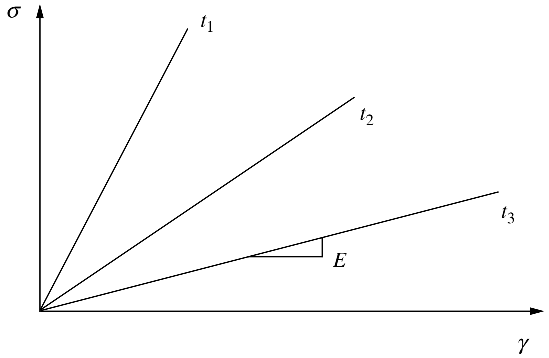

Fig. 2.13 Schematic view of the stress–strain relationship of a linear viscoelastic material at different times, corresponding to different deformation rates.

For linear materials, the stress is proportional to the strain. For linear elastic materials, Young's modulus (*E*), equal to the slope of the stress–strain curve, is constant. For viscoelastic materials, *E* is dependent on the deformation rate. A material is called linear viscoelastic if the stress is proportional to the strain, despite the time-dependence. In this case, the Young's modulus is a function of the deformation rate only. In Fig. 2.13, the stress–strain behavior of a linear viscoelastic material is shown schematically for different deformation rates, assuming that the material is exposed to a constant strain.

If the material is subjected to a time-dependent strain, the situation becomes more complicated. However, in the case of a linear viscoelastic material (like many food products) the superposition principle can be applied: the response of the stress to a strain increment is independent of the already existing strain. The effect of the strain as a function of time can therefore be integrated, and the generalized Hooke's law can be extended to describe the stress–strain behavior of linear viscoelastic materials relatively easily.

For linear viscoelastic materials the Young's modulus often decreases with decreasing deformation rate, or, which is equivalent, with increasing time. For many materials the Young's modulus decreases with temperature. In the case of food products, for which also the moisture content is important, the Young's modulus often decreases with increasing moisture content. In polymer science it was recognized that the effect of a higher temperature is often equal to the effect of a longer time (Ferry, 1961). By shifting the curves at different temperatures across the time axis a single master curve can be obtained. This leads to the advantage that one equation can be used for the effect of both time and temperature on the Young's modulus. For the effect of the moisture content the same procedure can be applied. A basic requirement for the use of shift factors is that they must be applicable to all the viscoelastic properties of a material, and so also to the failure strength. A material that has one time–temperature and time–moisture shift function is called thermo- and hydro-rheologically simple.

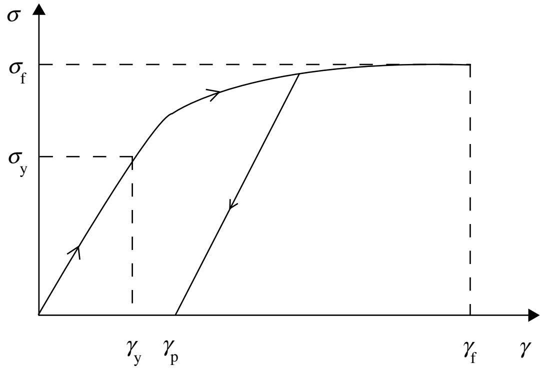

Fig. 2.14 Schematic view of the stress–strain relationship for an elastoplastic material. The symbols γ_y, γ_p and γ_f denote the yield strain, the plastic strain and the failure strain, respectively. The same notation is used for the stress σ.

Besides linear viscoelastic behavior, elastoplastic behavior is also often encountered for food products. In Fig. 2.14, the stress–strain behavior of an elastoplastic material is shown schematically. Because the stress–strain relationship is not linear and the strain does not recover if the yield stress is exceeded, the equations to describe this behavior are much more complicated.

The occurrence of stresses during drying is a result of non-uniform deformations of the material, which are caused by a combination of temperature and moisture gradients. The shrinkage behavior depends on the material characteristics. Two mathematically simple cases are uni-directional shrinkage and isotropic shrinkage. The shrinkage may be assumed uni-directional for the drying of thin constrained films. For clays and other inorganic materials the shrinkage can be considered as isotropic (Ketelaars, 1992).

2.4.2
Failure Strength in Rice Grains

The time-dependent Young's modulus and the failure stress of rice grains under compression were measured by Chattopadhyay and Hamann (1994) for constant deformation rates. Experiments with an oscillatory strain have also been carried out (Chattopadhyay *et al.*, 1978). Stress relaxation experiments were carried out by Chattopadhyay and Hamann (1994) and Yamaguchi *et al.* (1984). From these results, it appears that the Young's modulus decreases with increasing temperature and moisture content, which means that the material becomes softer: at equal deformations the stress is lower. The effect of temperature is stronger at lower moisture contents. At decreasing deformation rates (longer times), the Young's modulus decreases.

There is much less information available in the literature on the tensile strength of rice kernels, probably because measurements under tension are more difficult to realize than measurements under compression. For uniaxial tension tests, the kernels have to be fixed with adhesive at both extremities, in order to measure the failure stress in a tension testing apparatus. Arora *et al.* (1973) reported a value of 11.7×10^6 Pa for the tensile failure stress, at a temperature of 28 °C and for a moisture content of 12% (d.b). They did not publish results for other experimental conditions. Yamaguchi *et al.* (1984) reported a value of 2×10^6 Pa for the same moisture content, and a value of 8×10^5 Pa for 27% (d.b.), but the temperature was not given. Kunze and Choudhury (1972) measured the tensile strength of rice samples during moisture absorption. They found that the tensile strength decreased with the exposure time. Because there is a moisture gradient in the rice grains during these measurements, the obtained tensile strength data cannot be used for the modeling of stresses. However, it proves that the tensile strength of rice probably decreases with increasing moisture content, as is the case for semolina extrudates (Liu *et al.*, 1997). This result was confirmed by Kamst *et al.* (2002) on equilibrated rice materials.

Nguyen and Kunze (1984) applied a three-point bending principle to measure the tensile properties. This was not a true uniaxial tension situation, yet theoretically the failure would certainly indicate the failure of the tensile strength of the kernel (assumed as a loaded beam of cylindrical cross-section). The kernel was assumed sufficiently long, near homogeneous in structure, and approximately cylindrical in shape. The bending test is a simple test and maximum bending force has been proven to hold a good correlation with HRY (Lu and Siebenmorgen, 1995).

Kamst *et al.* (1999) transposed to rice grains a diametral-compression test (Peltier, 1954; Rudnick *et al.*, 1963) for measuring tensile strength. In this method, a horizontally placed cylinder is pressed between two flat plates. If proper load is applied, equally distributed along the cylinder (Fig. 2.15a), the maximum tensile stress becomes independent of the z-position between the two plates, and can be calculated as:

$$\sigma_t = \frac{2F}{\pi DL} \tag{2.1}$$

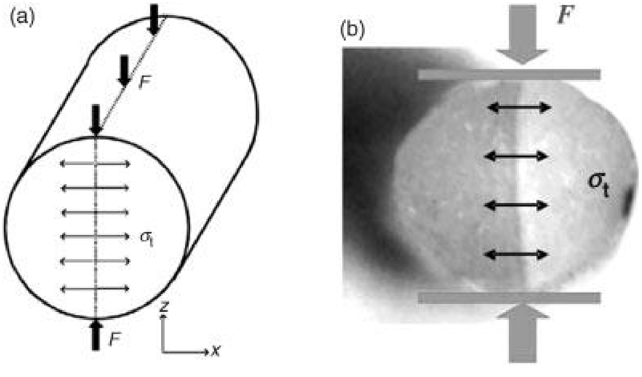

Fig. 2.15 (a) Schematic view and (b) cross-section of a rice kernel subjected to the diametral compression test.

with F the applied force, σ_t the tensile stress, D the cylinder diameter, and L the cylinder length (cf. with Sections 7.3.1.4 and 7.3.2 of this volume, as well as with Chapter 6 of Vol. 2).

Hulled, brown rice grains were cut at the two ends leaving samples that had approximately the shape of cylinders. Diametral-compression tests were carried out with an Instron type of machine, applying cross-head speeds of 0.1 and 0.01 mm min^{-1}, at 20 °C, with controlled RH. In these conditions, it has been checked that the failure took place along the diametral plane, dividing the grain into two equal half cylinders, which indicates that the fracture was only caused by a tensile stress (Fig. 2.15b).

The applied deformation rate was calculated by dividing the cross-head speed by the sample thickness, and the failure stress was defined as the first maximum of the stress–strain curve. The values of tensile strength measured in this way on kernels of 5.7% moisture content (w.b.) were in accordance with the literature (Kunze and Wratten, 1985), and significantly lower than the values of compressive strength measured by compressive uniaxial tests ($10 \pm 2 \times 10^6$ Pa as against $73 \pm 15 \times 10^6$ Pa, respectively). Kamst *et al.* (2002) used this test to measure the influence of the moisture content (at equilibrium) on the tensile strength (Fig. 2.16).

The results show a stable value of the tensile strength for moisture contents below 8.87% (w.b.), while at higher moisture contents (≥10%) this value declines with moisture content. A similar tendency was observed for the Young's modulus. Such an abrupt change in all measured mechanical properties could be explained by glass transition, inducing a distinct difference between brittle behavior at low moisture contents and ductile behavior at higher moisture contents. However, data in the literature indicate that glass transition occurs for much higher moisture contents (over 20% w.b.) at 20 °C (Perdon *et al.*, 2000; Cao *et al.*, 2004). Another explanation

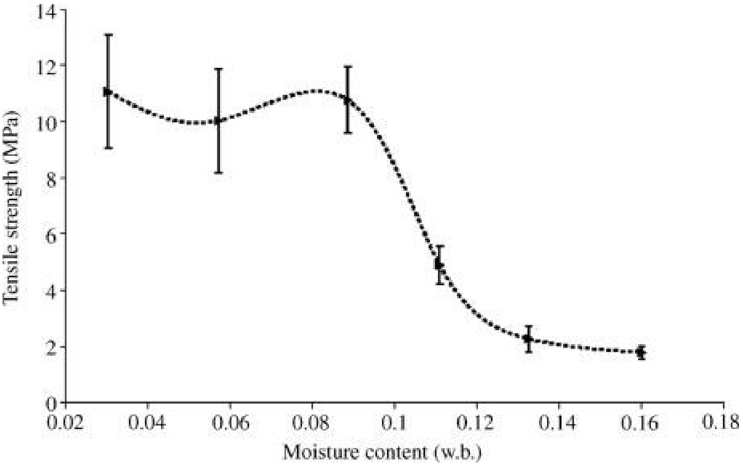

Fig. 2.16 Influence of the moisture content on the tensile strength of rice materials (Ariete cultivar), measured at 20 °C using the diametral-compression test, with a strain rate of $7 \times 10^{-3}\ \text{min}^{-1}$. Data from Kamst *et al.* (2002).

could be an increase in free water content within the kernel reducing the stiffness of the material (Wouters and De Baerdemaeker, 1988).

Parboiling under carefully controlled process conditions can enhance the tensile strength and tensile modulus of elasticity of rice kernels. Saif *et al.* (2004) found that parboiling increased the maximal tensile strength by almost four to five times compared to that of raw rice.

2.5
Modeling the Impact of Drying on the Final Quality of Rice Grains

There are several published papers dealing with the modeling of stress cracks in a rice kernel induced by drying. Two complementary approaches are usually used:

- Empirical curve fitting of experimental data with algebraic equations. This kind of model cannot render unsteady state conditions of drying, and cannot be extrapolated to other rice varieties since there are no physical parameters in the equation. Clearly, such models have little practical use.
- Finite element modeling based on the tensor of constraints and separately measured Young's modulus. This approach is highly meaningful, and can be extrapolated to other drying conditions and other varieties of rice kernels. On the other hand, the time-consuming single-kernel computations cannot be integrated in simulations of full-scale industrial dryers. Additionally, difficult laboratory measurements of mechanical properties of the rice kernel are required, along with restrictive assumptions concerning the kernel geometry, its homogeneity, and isotropicity.

A third – intermediate – way was used in Abud-Archila's work (Abud-Archila, 2000; Abud-Archila *et al.*, 2000). A global dynamic (differential) equation was built up on the basis of the core theory (as explained by Kunze and Choudhury, 1972). Using adequate experimental protocols, the empirical parameters were fitted, and the resulting equation was implemented in the commercial simulator Drying3000. Validation was provided by data measured in thin and thick layers, up to the industrial scale. This model can be considered as a compromise between physical meaning, practical usability, precision, and ability to represent a wide range of rice varieties and drying conditions.

In the mentioned work, q represents the HRY, and Q is the ratio $q(t)/q(0)$. Figure 2.17 shows the good repeatability of Q values measured by sampling at regular time intervals during a drying experiment. When removed from the dryer, the samples were cooled so as to preserve their characteristics, by slow ventilation at room temperature. Several drying experiments were carried out over a large range of drying conditions (40–80 °C, 0–99% RH). A first observation of results depicted in Fig. 2.18 would lead to the conclusion that drying air temperature is the main factor responsible for quality decay versus time. However, there is a hidden factor behind temperature: the evaporation capacity of the drying air (e.c.). This parameter is calculated as the distance in terms of air moisture content (in kg of water per kg of dry

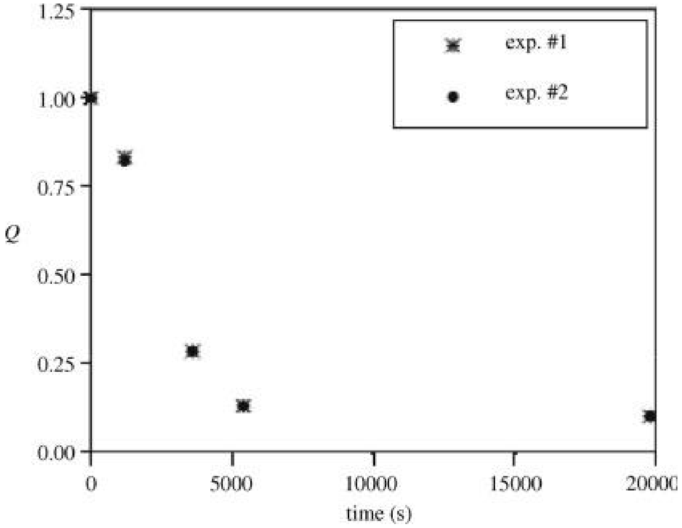

Fig. 2.17 Repeatability of quality kinetics of paddy rice ($T_a = 60\,°C$, evaporation capacity = 7.4 g of water per kg of dry air, $u_a = 1\ m\ s^{-1}$). Data from Abud-Archila *et al.* (2000).

air) between actual air and adiabatically saturated air. Figure 2.19 clearly shows, for two different air temperatures, that the e.c. has a major influence on the kinetics of quality decrease. Since a temperature increase leads to an e.c. increase, their effects are combined.

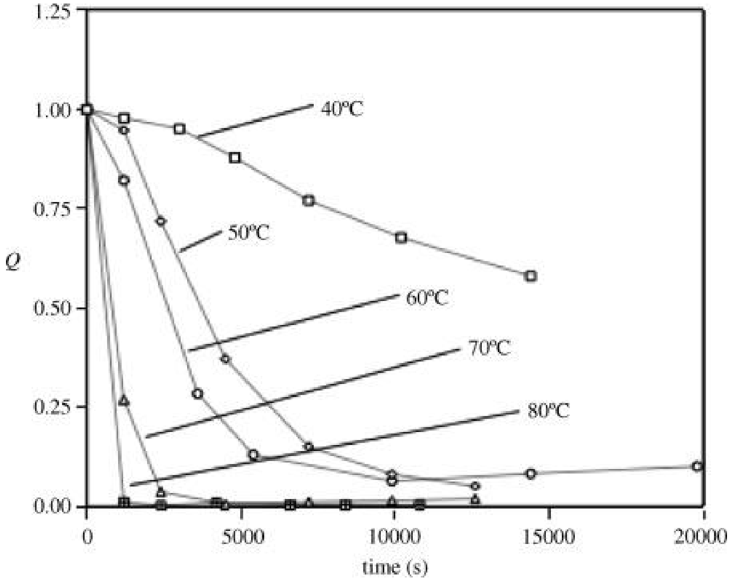

Fig. 2.18 Effect of air temperature on the kinetics of quality of paddy rice. All experiments were conducted with air having an evaporation capacity of 9 g of water per kg of dry air. Data from Abud-Archila *et al.* (2000).

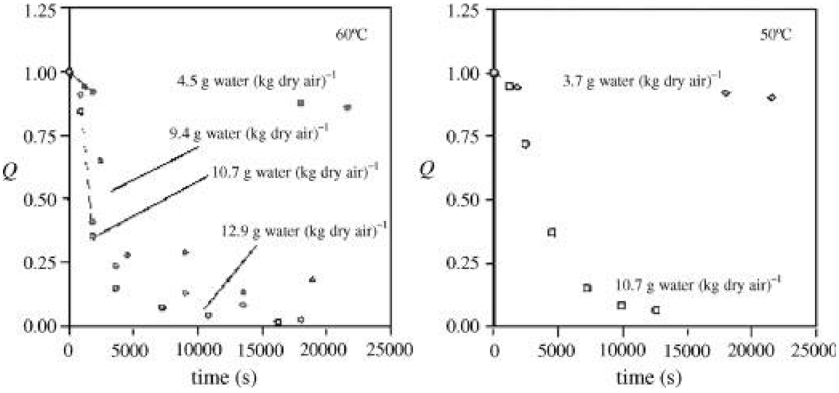

Fig. 2.19 Effect of evaporation capacity of the air on the kinetics of quality of paddy rice ($T_a = 50$ and 60 °C). Data from Abud-Archila *et al.* (2000).

The experimental raw data were transformed prior to modeling. Since there are a limited number of experimental points (about 7 per drying experiment), each kinetic curve was fitted with the following empirical equation:

$$Q = \frac{c_{10} \cdot \exp\left(\frac{t^2}{10^5 \cdot c_{11}}\right) + c_{12} \cdot \exp\left(\frac{t^2}{10^5 \cdot c_{13}}\right)}{c_{10} + c_{12}} \tag{2.2}$$

where c_{10} to c_{13} are empirical parameters obtained (one set per kinetic curve) by nonlinear curve fitting. Typical results are displayed in Fig. 2.20. Such a curve fitting

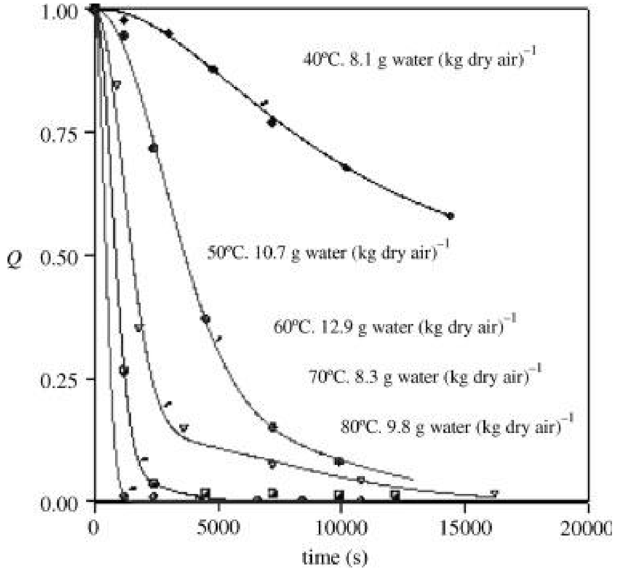

Fig. 2.20 Results of curve fitting on the experimental points of quality kinetics of paddy rice; Data from Abud-Archila *et al.* (2000).

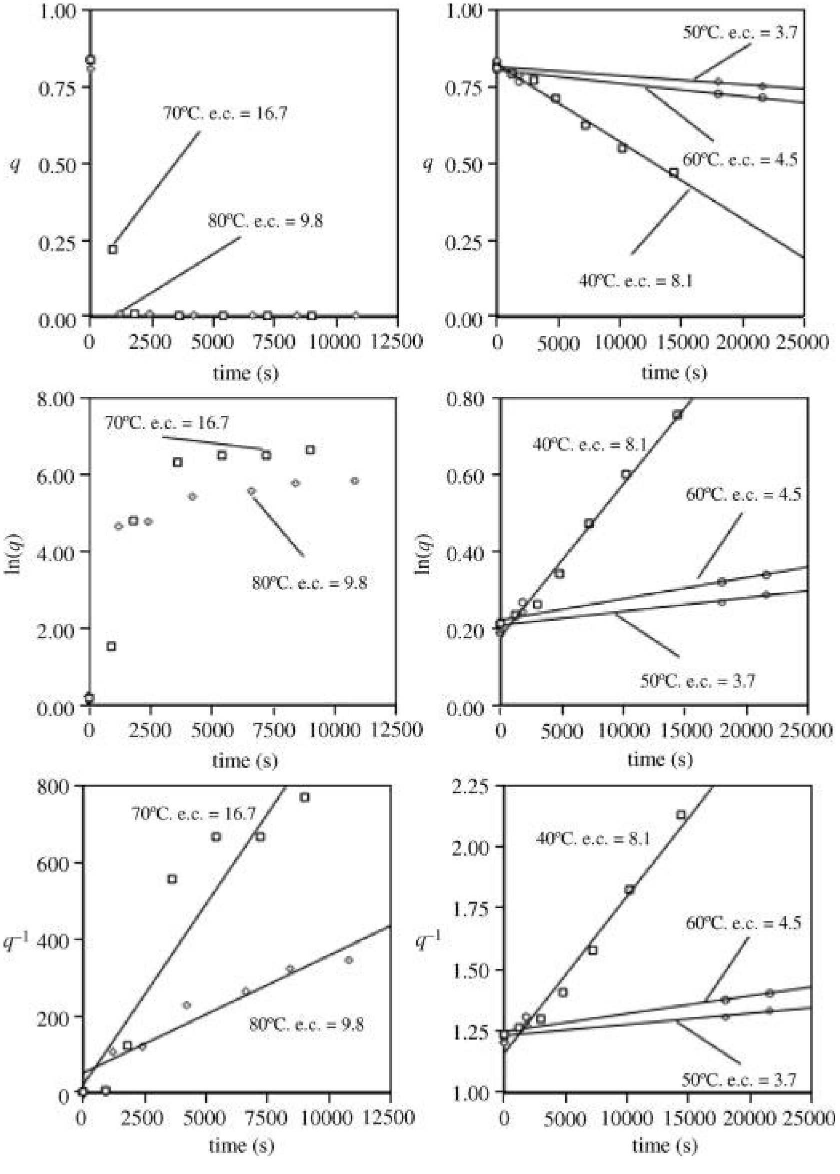

Fig. 2.21 Comparison of three different linearization techniques for the quality kinetics of paddy rice dried at temperatures ranging from 40 °C to 80 °C and evaporation capacities ranging from 3.7 to 16.7 g of water per kg of dry air. Data from Abud-Archila *et al.* (2000).

approach maximizes the usability of limited raw data, and minimizes the influence of abnormal values through smoothing.

The next step consists in finding the reaction order n in the following classical equation:

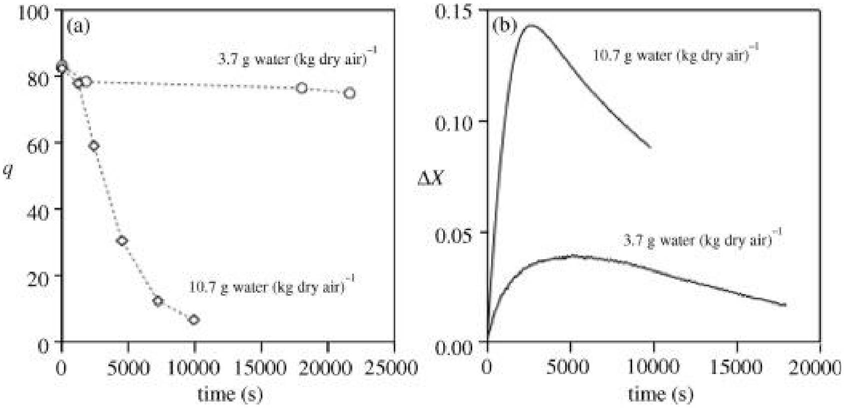

Fig. 2.22 (a) Experimental HRY (in %) kinetics at 50 °C for two different evaporation capacities; (b) estimated moisture content gradients for these two kinetics. Data from Abud-Archila *et al.* (2000).

$$\frac{\mathrm{d}q}{\mathrm{d}t} = -k \cdot q^n \tag{2.3}$$

where k is a parameter to be identified.

Figure 2.21 shows that the best linearization technique was obtained for $q^{-1} = q(t)$, that is, $n = 2$. The breakage of rice kernels during drying was thus assumed to behave like a second-order reaction.

Combined with a drying model simulating the moisture content gradient within the grain, ΔX (see Abud-Archila *et al.*, (2000); Courtois *et al.*, 2001), it is possible to compare the curve shapes of the quality kinetics with the corresponding moisture gradient kinetics. Figure 2.22 shows that the gradient is maximal during the first part of drying, when the evaporation flux is maximal. Furthermore, it is possible to compute the derivative of $q(t)$, and to compare it with the moisture gradient within the kernel, as suggested by many studies (Kunze and Choudhury, 1972). Using Eqs. 2.2 and 2.3, it is possible to compute the actual value of k:

$$k = -\frac{1}{q^2}\frac{\mathrm{d}q}{\mathrm{d}t} \tag{2.4}$$

Figure 2.23 compares the evolution of k and ΔX (the latter to the power 5). Using this simple correlation, and adding an Arrhenius law for the temperature dependence, one can conclude that a complete equation for quality loss kinetics might look like:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = -k_0 \cdot (\Delta X)^5 \cdot \exp\left(\frac{-E_\mathrm{a}}{R \cdot T_\mathrm{rice}}\right) \cdot q^2 \tag{2.5}$$

Here, k_0 is the pre-exponential factor, E_a the activation energy in the Arrhenius relation, R the ideal gas constant, and T_rice the rice grain temperature (in K).

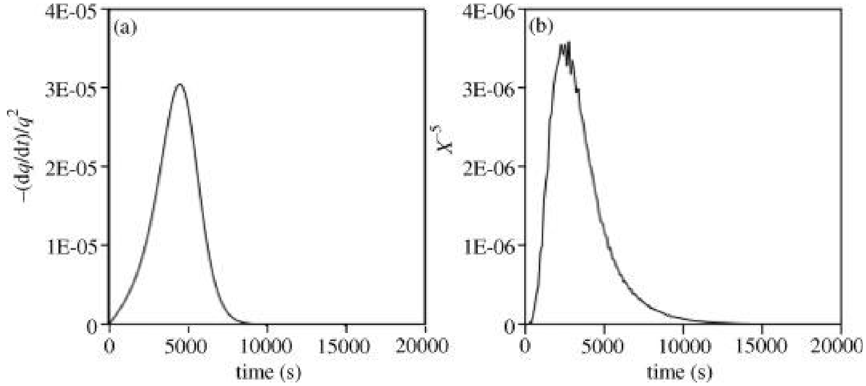

Fig. 2.23 (a) Estimation of $-(dq/dt)/q^2$ and (b) simulation of ΔX^5 as functions of time for a drying experiment of paddy rice at 60 °C and 7.4 g of water per kg of dry air (evaporation capacity). Data from Abud-Archila *et al.* (2000).

As depicted in Fig. 2.24, there is a very good agreement between experimental and simulated quality kinetics. In addition, it should be noted that the simulation of the quality kinetic is heavily reliant on the simulation of the rice temperature and moisture gradient, as computed by the underlying drying model.

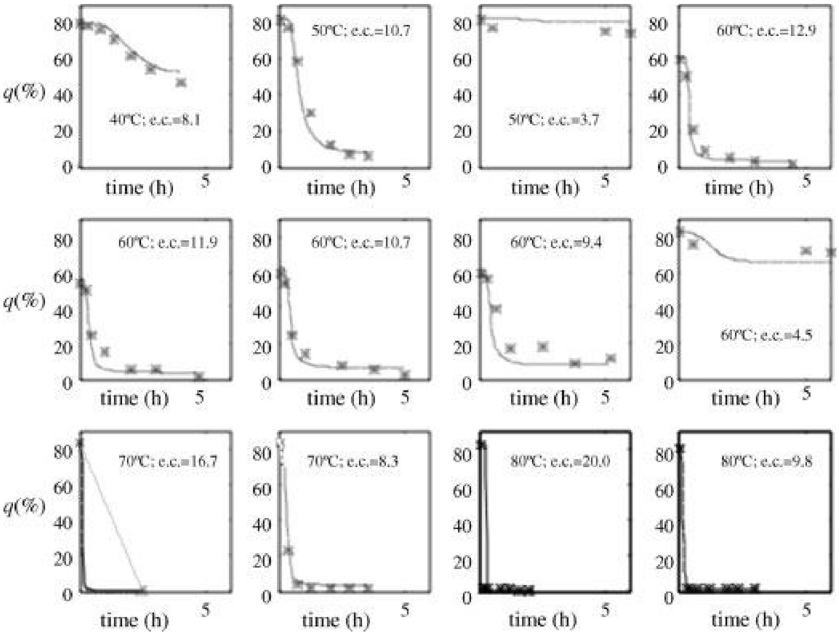

Fig. 2.24 Comparison between experimental (*) and simulated (–) HRY (%) kinetics for several paddy drying conditions; Data from Abud-Archila *et al.* (2000).

As shown here, such a modeling by analogy with a reaction kinetics approach gives a good prediction of HRY for paddy over a wide range of drying conditions. The model has been validated by comparison with experiments on thin and deep layers of grains, and on a large-scale semi-industrial dryer, for both steady and transient states (Courtois *et al.*, 2001). The whole model was included in the rice module of the simulator Dryer3000.

2.6
Conclusion

As pointed out in this chapter, the underlying mechanisms and conditions of fissuring and breakage of rice kernels are mostly well known. There is a wide range of literature published on the factors responsible for breakage of rice during milling. There are also numerous articles dealing with finite element – or volume – modeling and simulation of stress evolution within rice kernels. Nevertheless, quantitative data on the mechanical properties of rice kernels versus temperature and moisture content still need to be collected under properly controlled conditions, taking the cultivar variations into account. From a more practical point of view, or from an industrial perspective, the global approach presented in the last section is well adequate for the estimation of quality loss during drying under conditions of limited availability of measurements of the mechanical properties.

The image analysis techniques are now able to reliably quantify the breakage ratio (HRY) in a routine mode. Concerning the detection, quantification, and characterization of fissures, some advances have been presented and discussed here, but there is still much work to do before being able to regard it as a routine tool.

Additional Notation Used in Chapter 2

D	cylinder diameter	m
E	Young's modulus	Pa
F	force	N
L	cylinder length	m
T_g	glass transition temperature	K, °C
Q	$q(t)/q(0)$	—
q	head rice yield (HRY)	—

Greek Letters

γ	strain	—
σ	stress	Pa s

Subscripts and Superscripts

a	air
f	failure
p	plastic
t	tensile
y	yield

Abbreviations

d.b.	dry basis	
e.c.	air evaporation capacity	g water (kg dry air)$^{-1}$
HRY	head rice yield	
RH	relative humidity	
w.b.	wet basis	

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