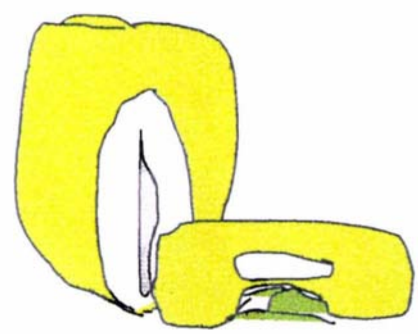
Physical changes in maize (*Zea mays* L.) grains during postharvest drying



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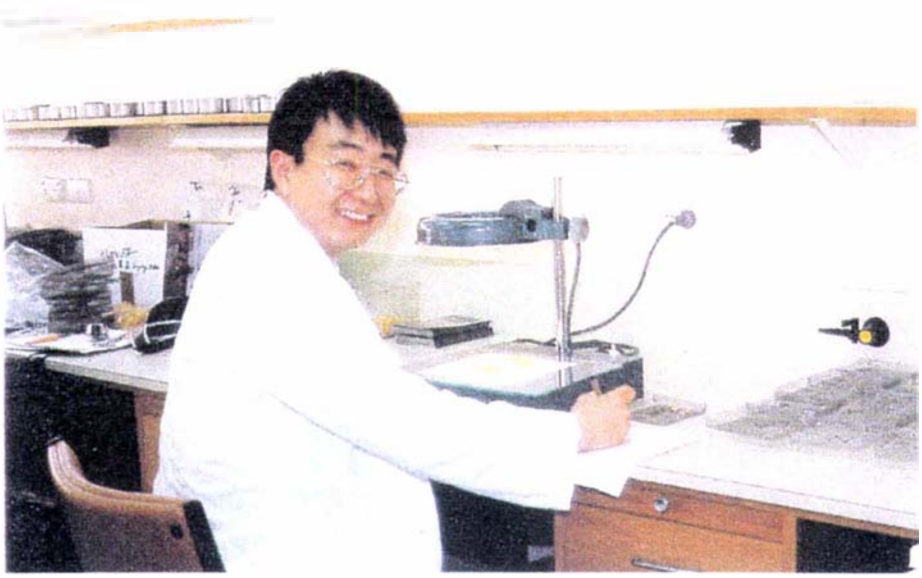

This thesis is dedicated to the four most inspirational people in my life,

my father, Kim In Goo,

my mother, Kwon Young Wha,

grandmother, Jung Bong Hee,

and my lovely wife, Kim Hyun Ok and

to the unforgettable memories in

New Zealand...

ABSTRACT

Stress cracking due to high temperature drying has been of concern to the maize industry because it can lead to increases in broken grain and fine material during subsequent handling. In this study, several factors affecting physical characteristics of maize grain, particularly those related to stress cracking, were investigated.

In the first year (1995-1996), the effects of several preharvest factors; hybrid, nitrogen, harvest grain moisture content, and postharvest drying factors including drying temperature and relative cooling rate on physical attributes and stress cracking in grain were investigated. Grain hardness (hard to soft endosperm ratio (H/S ratio)) was significantly affected by the interaction between hybrid and nitrogen. The effect of drying temperature and harvest moisture on drying time was dominant, while drying rate was significantly affected by hybrid and drying temperature. The effect of cooling rate on stress cracking and stress crack index (SCI) stood out among the main effects. At the lowest cooling rate of 0.23 (°C/°C/min.)•10^{-2}, checked stress cracking (checking) was minimal, and SCI was less than 100. However, at higher cooling rates from 0.55 to 1.11 (°C/°C/min.)•10^{-2}, grains had more than 25% multiple stress cracking, regardless of the levels of hybrid, nitrogen, harvest moisture and drying temperature. The predicted SCI for the three hybrids reached a maximum around at 0.75 (°C/°C/min.)•10^{-2} cooling rate, irrespective of levels of nitrogen and drying temperature.

In the second experiment (1996-1997), the effects of grain hardness and morphological factors (grain size and shape) at a single grain drying rate and the development stress cracking over time were investigated. The re-parameterized Morgan-Mercer-Flodin (MMF) model successfully predicted the increasing rate (κ) and the maximum value (α) of percentage checking in various sizes, shapes and hardness of grains time after drying. From the data analysis, the maximum value of checking (α) showed a significant correlation with grain length ($r = -0.707$), thickness ($r = 0.620$), roundness ($r = 0.703$) and the shortest diffusion pathway (SDP; $r = 0.627$). While, the increasing rate (κ) of percentage checking with time after drying was significantly correlated with

grain bulk density (r = -0.564), hardness ratio (r = -0.611) and drying rate (r = 0.551), and to a lesser extent (r > 0.35), with the grain size parameters including hundred-grain weight, grain length, and width. Based on this result, it was suggested that removing small and rounded grains could reduce checked stress cracking by up to 40 to 50% in some dent maize hybrids. In addition, the standardized multiple regression for single grain drying rate according to H/S ratio and grain weight accounted for from 65 to 74% of the variation. Tempering grain at high temperatures reduced stress-cracked grains significantly. However, the effect of tempering on stress cracking in the hard grain hybrid was small.

In the 1997-1998 experiment, a breakage tester (HT-I drop tester) was developed and single grain breakage at various grain temperatures and times after drying was determined. Both hard and soft maize hybrids had minimal breakage at high grain temperatures (78 to 110°C), while decreasing grain temperature increased breakage exponentially. This indicated that grain temperature should be considered as a co-factor for measuring grain breakage. After drying at both 60°C and 120°C, the percentage breakage measured at ambient temperature increased rapidly during cooling in air at an ambient temperature of 20°C and a relative humidity around 65-70%. Breakage reached a maximum after about 10 minutes from the start of cooling. A Mitscherlich function was used to describe the chronological development of percent grain breakage and the analysis of the function parameters for the extent (maximum) and rate of breakage indicated that there was a significant interaction between hybrid and drying temperature for the development of grain breakage after drying.

In conclusion, the MMF and Mitscherlich models described stress cracking and grain breakage during drying and cooling of maize grain. These studies provide valuable information to grain industries to assist with minimizing grain damage during drying.

Key words: maize, quality, stress cracking, breakage susceptibility, viscoelastic, hardness, postharvest drying, cooling, tempering, nitrogen, hybrid, harvest moisture, size and shape, breakage tester.

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Chapter 1 General Introduction

1-1. Introduction and background of research

Although most of the maize produced around the world is used for animal feed, its use for human consumption and the manufacture of industrial products has grown rapidly in recent decades (Good and Hill, 1992; Troyer and Mascia, 1999). Industries which use wet milling, dry milling or alkaline processing are looking for specific quality attributes in maize grain for producing the desired end products. For example, soft grains that have high starch contents are preferred for wet milling. For dry milling and alkaline processing (i.e., masa production), hard grains are preferred for making grits or various snack foods (Eckhoff and Paulsen, 1996).

Quality therefore has become a major concern in maize production and handling (Good and Hill, 1992). Several physical quality attributes of maize, such as grain hardness, the presence of stress cracking and breakage susceptibility which may affect maize processing, have been studied extensively (Watson, 1987a; Shandera et al., 1997).

Several studies have shown that physical attributes of maize such as grain hardness and breakage susceptibility are inherited characteristics, can be improved by breeding, by proper selection of a hybrid, and by cultural practice (Johnson and Russell, 1982; Paulsen et al., 1983b; Bauer and Carter, 1986). For example, higher nitrogen application levels increased grain hardness, apparently reduced breakage susceptibility, and thus could improve maize dry milling quality (Sabata and Mason, 1992; Ahmadi et al., 1995; Patwary, 1995; Oikeh et al., 1998).

However, high quality of maize could not be achieved unless grains were properly harvested and dried. In modern agriculture drying is considered the most important postharvest process that influences maize quality (OTA, 1989; Brooker et al., 1992). Increases in stress cracking and grain breakage due to improperly controlled drying such as conventional high temperature drying often causes an increase in broken grain and fine material during subsequent handling, thus decreases maize end use quality (Watson, 1987a).

It is very important to understand the factors that affect the physical characteristics of maize, such as stress cracking, so that maize quality can be improved through better crop management and postharvest handling, thus ensuring high quality maize for the food industries.

1-2. Objectives of this thesis

The aim of this research was to examine 1) some of the agronomic management factors, and 2) postharvest drying factors that may affect physical characteristics of maize grain. The overall objective was to investigate physical characteristics of maize grain, especially stress cracking, during postharvest drying. The specific objectives of this thesis were to:

a) evaluate the incidence of stress cracking of three commercially grown maize hybrids as affected by nitrogen fertiliser applications to the crop and postharvest drying treatments;

b) determine the effects of grain size/shape and hardness on grain drying rate and the development of stress cracking in maize grain over time after drying; and

c) develop and evaluate a breakage tester for testing single maize grain breakage at various grain temperatures and times after drying.

Chapter 2 Literature Review – Agronomic and postharvest drying factors affecting physical properties and stress cracking in maize grain

2-1. Introduction – background, scope, and the objectives of this review

2-1-1. Background – trends in maize use and quality traits for end users

Maize (*Zea mays* L.) is the world's most widely distributed crop and is especially important in Latin and Central America and many countries of Africa and Asia where it is the main source of energy and an important source of protein (Serna-Saldivar et al., 1992; Brown and Begin, 1993). While most of the maize produced around the world is used for animal feed, its utilization for human consumption for food and industrial products has grown rapidly in recent decades (Good and Hill, 1992; USDA, 1996). As a result of improved maize breeding (Duvick, 1992) and production technology over the past decades, maize production has continued to increase (Mann, 1999; Reetz, 1999). A relatively stable supply and cheap price has resulted in increasing and diversifying food and industrial uses of maize (Watson, 1988; Troyer and Mascia, 1999). Due to these trends, quality has become a major concern, especially for maize used for human consumption (Good and Hill, 1992).

Quality of maize has been broadly defined as grain soundness and viability as determined by various tests from simple visual appearance to the more complicated laboratory tests (Watson, 1987a). Most nations have national grades and standards, the main objectives of which are 1) to facilitate marketing and 2) to identify economic values to the end users (Hill, 1988). The most frequently measured quality factors in the US grades and standards are test weight, BCFM (Broken Corn and Foreign Material), and damaged grains including machine damaged and heat damaged grains (USDA, 1988). However, standards differ from country to country (Paulsen and Hill, 1985b; Bender et al., 1992). Although these maize grading factors are still important to end users, they do not describe the desired maize quality for each specific end user because the important characteristics differ with different end users and for different products (Butz, 1975; Watson, 1987a; Good and Hill, 1992). For example, broken grains may be unacceptable to the starch producer (wet miller), but may be of little concern to the producer of livestock feed who intends to grind the product (Butz, 1975). Therefore each industry and each individual user within an industry has come to rely on numerous tests that subjectively predict a particular process and product (Freeman, 1973; Paulsen and Hill, 1985a; Shandera et al., 1997). For example, grain hardness, an important intrinsic property that affects wet- and dry-milled products is not included in most grades and standards (Watson, 1987a).

Wet milling is an aqueous processing technique, which separates maize into its chemical constituents and it aims at a high yield of starch (Anderson, 1970; May, 1987). Dry milling, on the other hand, involves mechanical grinding and sieving to separate grain into its components: endosperm, bran, and germ, and thus it targets the physical attributes rather than chemical attributes that will produce a high yield of flaking grits (Brekke, 1970; Alexander, 1987; Eckhoff, 1992a).

Generally, wet millers prefer to use soft endosperm maize with a high starch content, while dry millers generally prefer maize with a high proportion of hard endosperm (Wichser, 1961; Brekke, 1970; Watson, 1988; Eckhoff and Paulsen, 1996). However, both processing techniques desire lower breakage susceptible grains, which can be achieved by proper hybrid selection with appropriate crop management and postharvest handling (Foster, 1975; Salunkhe et al., 1985; Herum, 1987; Brooker et al., 1992; Kettlewell, 1996; Mills, 1996).

2-1-2. Scope – Quality maintenance and importance of drying

Physical quality characteristics in maize, such as grain hardness and breakage susceptibility, are of particular importance for a specific milling industry (Paulsen, 1992; Shandera et al., 1997). Grain hardness and breakage susceptibility are known as heritable characteristics that can be changed by breeding or proper selection of hybrids (Paulsen et al., 1983b; LeFord and Russell, 1985; Stroshine et al., 1986). These factors are also influenced by several cultural management variables such as sowing date, soil nitrogen availability, water regime, plant density, and harvest grain moisture levels (Bauer and Carter, 1986; Moes and Vyn, 1988; Ahmadi et al., 1995).

However, since maize grain lots are sequentially harvested from the field and often stored for some time before use, high quality can not be guaranteed if the crop is not properly harvested and handled after harvesting. The most important postharvest management factor for maintaining quality of maize is the drying process. Of the overall management factors, drying uses a large amount of energy, and the effect of drying on the physical properties of the grain can be devastating (OTA; 1989; Brooker et al., 1992; Loewer et al., 1994). If the drying process is not properly controlled, internal grain fissures, stress cracking, may occur, and make the grain more susceptible to breakage (Thompson and Foster, 1963). Increasing grain breakage susceptibility due to improperly controlled drying results in an increase in broken grain and fine material during subsequent handling, and finally lowers the maize grades and milling quality (Watson, 1987a).

It is therefore very important to understand the effects of cultural practice and postharvest management, especially the drying process, on grain quality, so that maize producers can be provided with relevant information to establish management strategies to ensure the desired quality attributes in grain for special industrial uses.

2-1-3. Scope and objectives of this review

Modern cultural practice and postharvest management skills have improved maize quality, but more information is still required to allow a maintenance of better quality through reducing the negative effects of poor management practice. This review is focused on those aspects of agronomic management and postharvest drying which affect physical attributes of maize grain, especially quality attributes needed for industrial utilization for human consumption including wet milling, dry milling and alkaline processing. The most important of these quality characteristics are physical, particularly grain hardness, breakage susceptibility and stress cracking.

The objectives of this review are: 1) to provide the basic terminology to understand the industrial uses of maize grain including its structure and the types of maize; 2) to define the desired quality attributes for milling industries for food use; 3) to define grain standards and describe quality measurement techniques; and finally 4) to discuss the effects of agronomic and postharvest drying factors on the physical characteristics of maize grain including hardness, breakage and stress cracking.

2-2. Terminology

2-2-1. Structure of maize grain

The maize grain (or kernel) is classified botanically as a caryopsis, i.e., a single-seeded fruit, in which the fruit coat (pericarp) does not separate naturally from the seed (Wolf et al., 1952a; Inglett, 1970b; Watson, 1987b). Due to its unique structure and composition, maize is broadly useful as an animal feed and food grain and has specific industrial value (Watson, 1988). A precise knowledge of the structure and composition of the mature maize grain is necessary for understanding how it can be processed and efficiently utilized (Watson, 1987b). For the purpose of this review, the structure of dent maize (see 2-2-2A), which is the major source of maize for most milling industries, will be described, unless otherwise noted.

Mature maize grains are composed of four major parts: pericarp (hull or bran), germ (embryo), endosperm, and tip cap (Eckhoff, 1992a; Hoseney, 1994). However, for many industrial processes, maize grain is separated into the three main parts of the grain (Wolf et al., 1952a; Eckhoff and Paulsen, 1996): pericarp, endosperm, and germ (Figure 2-1).

A. Pericarp

The pericarp or hull (Figure 2-1), the true fruit coat of the maize grain (Watson, 1987b), is the outer protective covering composed of dead cells that are primarily cellulose and hemicellulose (Wolf et al., 1952b). The pericarp protects the grain from deterioration by resisting penetration of water, and from microbial infection and insect infestation (Eckhoff, 1992a). The pericarp makes up 5-6% of the grain dry weight (Watson, 1987b). The detailed structure of the pericarp was illustrated by Wolf et al., (1952b). Pericarp thickness is inheritable and it differs with genetic background, but not with harvest moisture of grain (Helm and Zuber, 1970). Helm and Zuber (1969) found that pericarp thickness varied from 62 to 162 μm in 33 maize inbred lines and they showed that it could be controlled by breeding (Helm and Zuber, 1972).

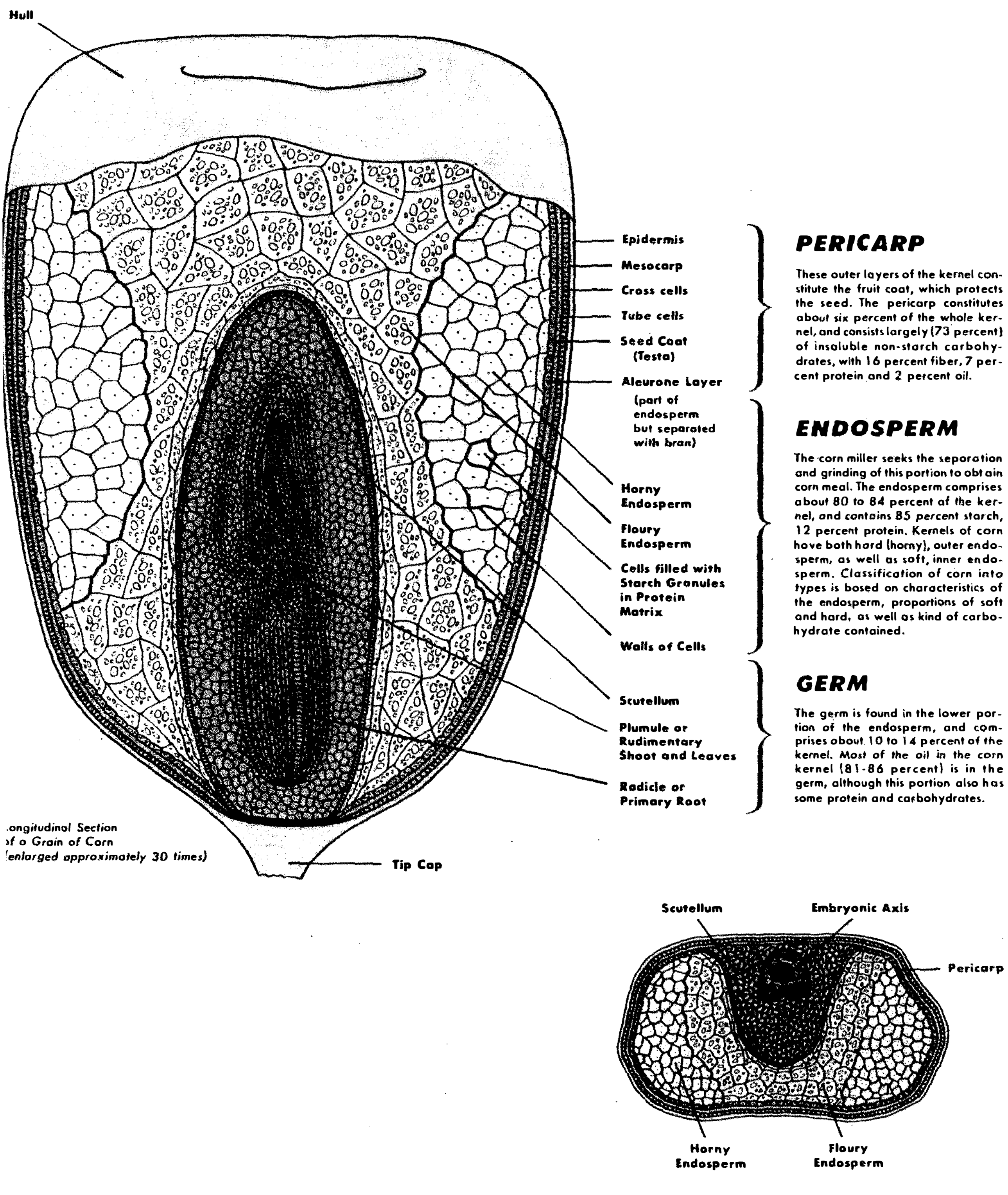


Figure 2-1. Longitudinal and cross sections of a maize grain enlarged approximately 30 times (FAO, 1984).

The term, "bran", is sometimes used to describe the pericarp-containing product of a dry-milling or wet-milling process that includes the tip cap, aleurone layer, and adhering pieces of starchy endosperm (Watson, 1987b). In the wet-milling process it is termed "fibre" (Watson, 1987b).

B. Tip cap

The pericarp extends to the base of the grain, uniting with the tip cap (Figure 2-1). The tip cap is the smallest fragment that connects the grain to the cob (Wolf et al., 1952a). The tip cap, a cone-shaped distinct part of the pericarp, which has spongy- or star-shaped cells well adapted for rapid moisture absorption (Wolf et al., 1952b), plays a major role in seed germination and in the processing of the grain. As the attachment for the maize grain to the cob, the tip cap area is the major pathway of components into the grain from the maize plant (Eckhoff and Paulsen, 1996).

The tip cap constitutes about 1% of grain dry weight (Watson, 1987b). Pulling the tip cap off exposes a dark brown circular layer, known as the hilar or black layer, that seals the tip of the grain (Bradbury, et al., 1962; Watson, 1987b). The black layer appears at shortly after the grain maturation and cessation of dry matter accumulation (Daynard and Duncan, 1969; Watson, 1987b).

C. Germ

The germ is composed of the embryo and the scutellum (Figure 2-1) and it contains genetic information, enzymes, vitamins, and minerals for germination (Watson, 1987b; Eckhoff, 1992a). The germ comprises about 10 to 14% of the weight of the grain in different varieties of maize (Wolf et al., 1952a). The detailed structure of the germ has been shown by Wolf et al., (1952d) and Watson (1987b).

From the perspective of processing of the maize grain, the germ is important for two reasons (Eckhoff and Paulsen, 1996): 1) the germ is a concentrated source of oil and 2) the germ has a higher rate of moisture absorption than the other parts of grain components and acts as a pathway into the endosperm during water absorption (Ruan et al., 1992).

D. Endosperm

The endosperm (Figure 2-1) comprises about 80 to 84% of the grain dry weight (Wolf et al., 1952a) and is the source of energy and protein for the germinating seed (Eckhoff, 1992a).

The structure of maize endosperm is very important for maize processing industries (e.g., dry milling and wet milling) because it must be broken into particles of the desired size during the milling process (Wolf et al., 1952c) for the production of various food and industrial products. Maize endosperm consists of an aleurone layer which is a thin outer layer containing pigments, oil and protein and a large inner portion of starch granules embedded in a continuous protein matrix (Wolf et al., 1952c; Christianson et al., 1969; Watson, 1987b) (Figure 2-1). Starch granules are spherical shapes and their sizes range from approximately 5 to 30μm in diameter (Watson, 1987b, Figure 2-2). The protein matrix is composed of an amorphous protein material known as "glutelin" (Eckhoff and Paulsen, 1996), where distinct protein bodies are embedded (Watson, 1987b). "Zein", an alcohol soluble protein, which is extremely low in lysine, is a major composition of the protein bodies. Wolf et al., (1952c) and Watson (1987b) extensively reviewed and illustrated the detailed microscopic structure of the protein matrix and starch granules in maize endosperm (see also Figure 2-2).

Maize endosperm is composed of two types, hard (also called horny, corneous, vitreous, or translucent) and soft (also called floury or opaque) (Watson, 1987b; Eckhoff and Paulsen, 1996). In most dent maize hybrids, hard endosperm is found around the sides and back of the grain (Figure 2-1), while soft endosperm is located in the centre and crown of the grain (Eckhoff, 1992a). In hard endosperm, starch granules are tightly packed together, each held firmly in a protein matrix (Figure 2-2) which remains intact during drying (Watson, 1987b).

Although the protein matrix also surrounds each starch granule in soft endosperm cells, it is thinner than that in hard endosperm (Figure 2-2). During desiccation, the thin protein matrix in soft endosperm ruptures, causing air pockets that are points of weakness. These air pockets reduce translucency, producing an opaque appearance in soft endosperm (Duvick, 1961).

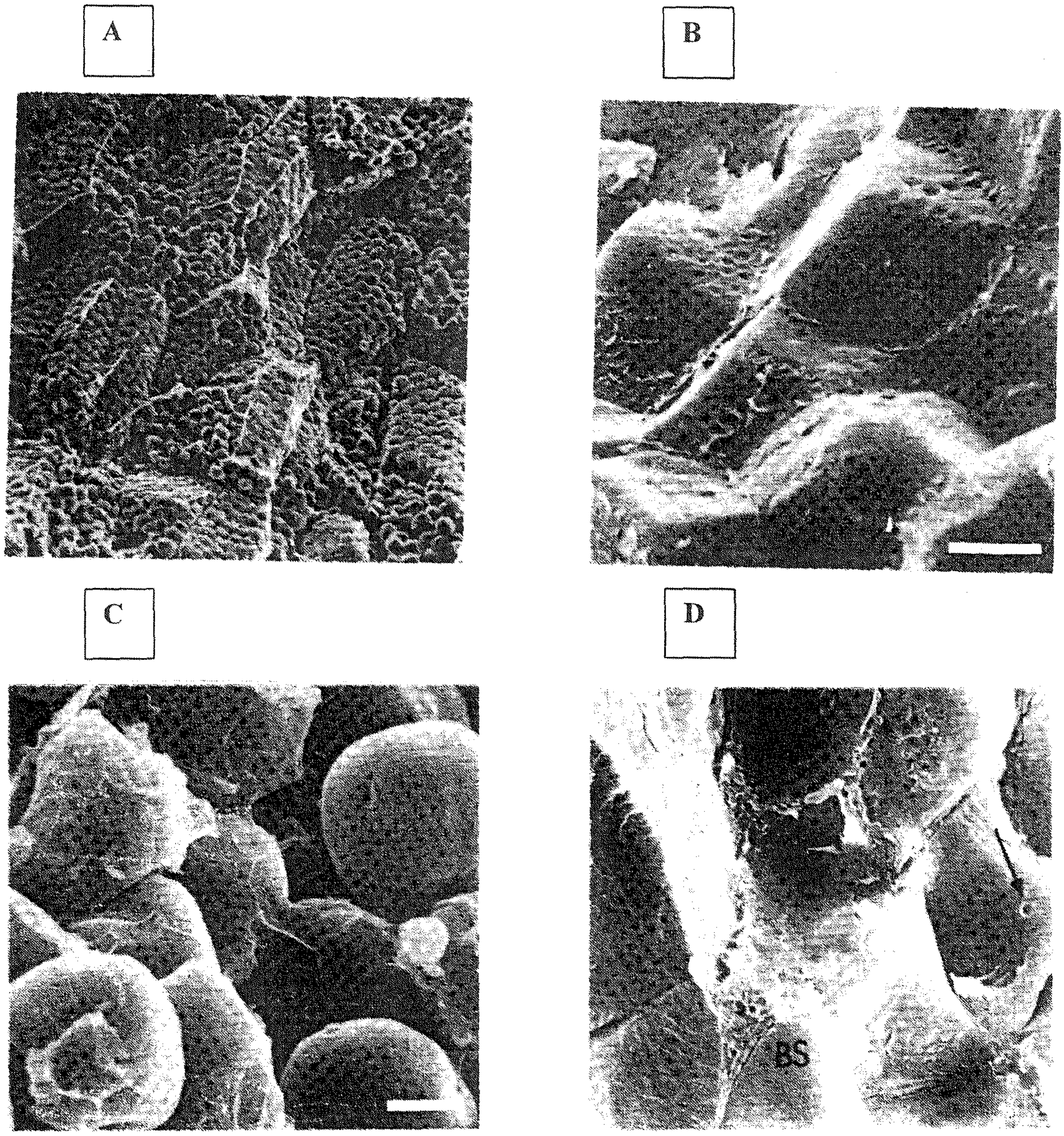


Figure 2-2. Scanning electron micrographs of maize grain endosperm (Hoseney, 1994).

Note: Each bar is 5 μm. A: a broken grain, showing the cellular nature of the endosperm. B: Cross section of the vitreous (hard) endosperm in maize grain, showing the polygonal shape of the starch granules, the indentation in the starch, and the tight compact structure. C: Cross section of the opaque (soft) endosperm, showing the spherical shape of the starch granules, the protein, and the large amount of air space. D: Cross section of the hard endosperm, showing the starch hilum (the point from which the starch granule grew, arrow) and broken starch (BS).

Quantities of the hard and soft endosperm area differ depending on genetic background (Inglett, 1970a; Watson, 1987b). Generally, for normal dent maize, the ratio of hard to soft endosperm is about 2:1 (Inglett, 1970b). In maize classification according to grain characteristics, flint maize and popcorn have a high proportion of hard endosperm (Figure 2-3). Flour (or opaque) maize has no hard endosperm and is soft (Figure 2-3). The dent maize, which is a main source for milling industries, is intermediate (Pomeranz et al., 1984). However, the ranges of hardness within each type of maize are related to the differences in horny-floury ratios and pericarp thickness and cell structure (Szaniel et al., 1984, Li et al., 1996), which are influenced by environmental factors during grain development such as moisture, temperature and soil nitrogen availability and its uptake into the grain (Hamilton et al., 1951; Kettlewell, 1996). Further details of the effects of these conditions on grain hardness will be discussed later.

2-2-2. Varieties of maize and their use

Maize originated from Central Mexico (Mangelsdorf, 1974; Benson and Pearce, 1987; Galinat, 1988; Johnson, 1991) and is today widely grown as an annual crop for both grain and herbage fodder. Corn, a synonym of maize, is the common name for maize in the USA and neighbouring countries, but this term is confusing as it is also used for wheat in England and for oats in Scotland (Inglett, 1970b; Claridge, 1972). Maize has a wide range of genetic diversity (Eckhoff and Paulsen, 1996). It is considered to have originated from a wild relative plant, teosinte (*Zea mexicana*) (Mangelsdorf, 1974; Galinat, 1988) and various types of maize exist on a regional basis (Goodman and Brown, 1988; Sánchez and Goodman, 1992). However, in general maize can be divided into five commercially important groups based on grain characteristics: dent, flint, pop, flour and sweet maize (Figure 2-3).

A. Dent maize

Dent maize (*Zea mays indentata*) is the most widely grown type of maize (Watson, 1987b). Dent maize gets its name from a characteristic dent in the crown area of the grain that occurs during maturation and drying (Watson, 1987b; Johnson, 1991; Eckhoff and Paulsen, 1996) (see also Figure 2-3).

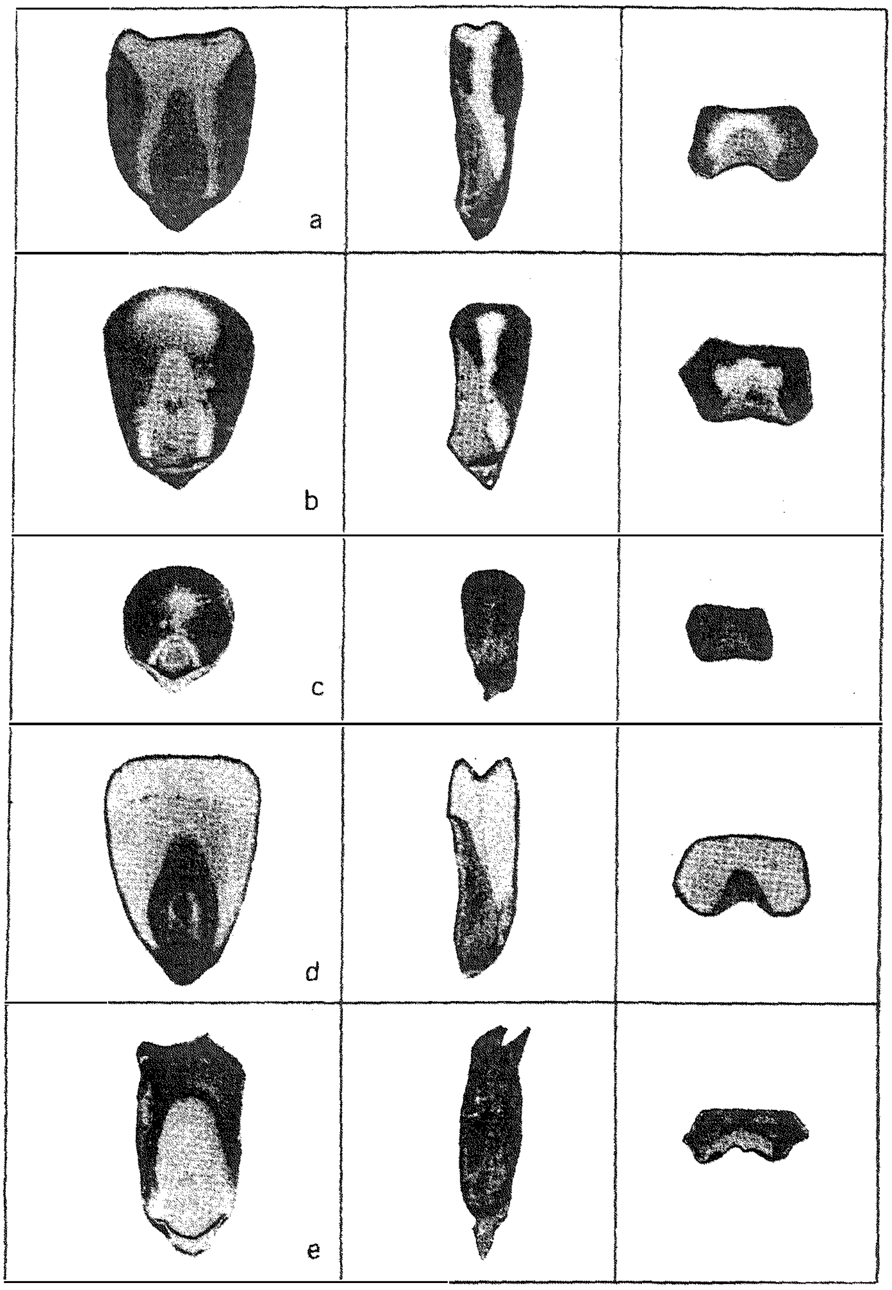


Figure 2-3. Various types of maize grains (Watson, 1987b).

Note: a, dent maize; b, flint maize; c, pop maize (popcorn); d, flour maize; e, sweet maize. Left column, longitudinal section parallel to germ front; centre column, longitudinal section perpendicular to germ front; right column, cross section. All sections were cut approximately through the median line (enlarged approximately two times).

The distinct indentation in the crown results from the collapse of the protein matrix in the floury endosperm in the central area of the grain. This region is too weak to support itself during dry down, collapses, and pulls the pericarp at the crown toward the centre of the grain (Duvick, 1961; Eckhoff and Paulsen, 1996).

Since dent maize originated from the hybridization of flour and flint types of maize (Galinat, 1988), the ratio of hard to soft (or horny to floury) (H/S or H/F) endosperm varies significantly with hybrid (Watson, 1987b). Furthermore, H/S ratio of individual grains differs within a hybrid due to environmental factors during grain development (Hamilton et al., 1951; Watson, 1987b).

B. Flint maize

Flint maize (*Zea mays indurata*) has a thick, hard vitreous endosperm which surrounds a small amount of soft or floury endosperm (Johnson, 1991; Eckhoff and Paulsen, 1996). It thus shows no denting during drying and maturation and looks smooth and rounded (Eckhoff and Paulsen, 1996; Zuber and Darrah, 1987, see Figure 2-3).

Flint maize is grown extensively in Argentina and other areas of South America and Latin America. In these regions, various races of flint maize have been grown and variously known as 'Cuban Flint' in the Caribbean, as 'Cateto' in Brazil, and as 'Argentine Flint' in Argentina (Goodman and Brown, 1988; Hameed et al., 1994b). These flint maize races are used to produce high-yielding hybrid combinations with dent maize in the U.S. and to improve physical grain quality attributes of dent maize (Goodman and Brown, 1988; Hameed et al., 1994b). Although Argentine flints are better suited for feed and dry milling than dent maize, they are less suited for wet milling because hardness and high protein are the two most negative quality factors for wet milling (Johnson et al., 1989).

C. Pop maize

Pop maize (*Zea mays everta*) is a small flint maize type (Watson, 1987b, Figure 2-3) and is the most primitive race of maize (Johnson, 1991). Pop maize is characterized by a very hard, corneous endosperm and is usually grown for use as a snack food, which is popped and eaten with salt and butter or other added flavours, and is now increasing in consumption (Pollak and White, 1995). When the grains are rapidly heated, moisture in the hard endosperm vaporizes but is unable to escape due to the low diffusive property of the thick dense protein matrix encasing the starch granules (Hoseney et al., 1983). The vapour congregates at a pin hole size void located at the centre of each starch granule (see Figure 2-2). When the pressure inside the grain exceeds the mechanical strength of the grain, popping occurs (Hoseney et al., 1983; Eckhoff and Paulsen, 1996).

The popping expansion volume of grain depends on several genetic and quality factors. Rounder grains are normally more effective for popping due to the diffusion path lengths for vapour escape, and larger grains have higher expansion values (Song et al., 1991; Song and Eckhoff, 1994). The pericarp also plays a major role in the complete expansion of the grains since it acts as a barrier against diffusion of water vapour and thus any pericarp damage decreases the expansion volume (Kim et al., 1995; Eckhoff and Paulsen, 1996). In premium quality pop maize, the popping volume (bulk density of the popped grains) reaches over 48 cm^3/g (Eckhoff and Paulsen, 1996). Hard endosperm dent or flint maize can also pop to a limited extent, depending on the diffusive character of the endosperm (Eckhoff and Paulsen, 1996).

D. Flour maize

Flour maize (*Zea mays amylacea*) is one of the oldest types of maize and is characterized by a lack of hard endosperm (Zuber and Darrah, 1987; Johnson, 1991; Eckhoff and Paulsen, 1996). It is not grown commercially to any extent, but it was used extensively by the American Indians because it is soft and easily ground into a meal (Claridge, 1972; Zuber and Darrah, 1987). The grains of flour maize are generally large and flat (Figure 2-3). During drying the endosperm tends to shrink uniformly and as a result no denting of the grain occurs (Eckhoff and Paulsen, 1996). This type of maize is grown widely in the Andean region of South America but very little is grown elsewhere (Zuber and Darrah, 1987).

E. Sweet maize

Sweet maize (*Zea mays saccharata*) has some recessive genes which inhibit the conversion of sugar into starch during grain maturation (Zuber and Darrah, 1987; Watson, 1987b; Eckhoff and Paulsen, 1996). Thus it accumulates sugar in the endosperm and has a sweet taste when consumed about 18-20 days post-pollination

(Zuber and Darrah, 1987). Most mutant genes affecting sweet maize are recessive. Therefore, sweet maize must be isolated from foreign pollen sources that would have a xenia effect resulting in starchy endosperm (Zuber and Darrah, 1987). Sweet maize (or sweet corn) now has become popular as a 'vegetable' for humans, being consumed fresh or commercially processed for canned and frozen products (Pollak and White, 1995). Its genetics and breeding were discussed by Marshall (1987).

F. Other grain characteristics

As mentioned, maize grain characteristics are diverse due to differences in endosperm composition that can be changed by a single gene, such as those between floury (*fl*) versus flint (*Fl*), sugary (*su*) versus starch (*Su*), or waxy (*wx*) versus non-waxy (*Wx*) (Zuber and Darrah, 1987). The dent maize and the flint maize endosperm carry dominant genes and normal amounts of starch with normal starch properties (Watson, 1987b).

Other commercially important endosperm characteristics in maize have been found and developed through genetic modification or enhanced specific compositions: 1) starch modifications for waxy (*wx*-gene) and high-amylose maize (*ae*-gene) (Vineyard et al., 1958), 2) protein modifications for high-lysine (o_2 or fl_2- gene) (Mertz et al., 1964) or QPM (quality protein maize) (Villegas et al., 1992; Mertz, 1992), and 3) germ oil enhancement for high-oil maize hybrids (Alexander and Creech, 1988; Alexander, 1999).

Further information about maize mutants, breeding mechanisms, and history of those modifications can be found in Zuber and Darrah (1987), Alexander and Creech (1988), Mertz (1992), and Neuffer et al., (1997). In addition, various colours of maize grains exist due to genetic differences in pericarp, aleurone, germ, and endosperm (Neuffer et al., 1968; Watson, 1987b); these range from white to yellow, orange, red, purple, and brown. Only yellow or white dent maize is grown commercially (Watson, 1987b) while 'Argentine flint' has orange-red endosperm.

2-3. Maize milling industries and the maize quality attributes desired

2-3-1. Milling industries – processing procedure and products

Most maize grown in many western countries is used for animal feeding. Nearly 80 percent of maize in US (Pollak and White, 1995; USDA, 1996) and 70 percent in New Zealand (Logan, 1994; Dunbier and Bezar, 1996) is used for animal feed. However the proportion used for feed is reducing. The fastest growing use of maize today in many countries is for food and industrial products (Troyer and Mascia, 1999). These maize processing industries are looking for specific quality attributes in grain for producing the desired end products. However the desired quality attributes differ for each processing industry, due to differences in processing methods and end products (Good and Hill, 1992). Therefore, it is important to understand the basics of maize processing technologies and their products in order to define the quality traits in grain for these industries. Animal feed use and quality characteristics are not considered in this review.

The most important commercial processes that convert raw maize into food and industrial products are wet milling, dry milling, and alkaline processing.

A. Wet milling

Wet milling is an aqueous processing which separates maize into its chemical constituents i.e. starch, protein, fibre, and oil. It provides a much cleaner separation of the germ and pericarp than other milling processes (Chappell, 1985; Pollak and White, 1995; Eckhoff and Paulsen, 1996). However, wet milling is a complex, energy- and capital-demanding process (Pomeranz, 1987; Eckhoff and Paulsen, 1996).

The main steps of wet milling are; 1) steeping (i.e., hydration of grains in sulphur dioxide (SO_2, 0.1-0.2%) solution at elevated temperatures (45-55^{o}C) held for about 20-50 hours (May, 1987; Hoseney, 1994; Eckhoff and Paulsen, 1996)) and germ separation, 2) fibre washing and drying, 3) starch gluten separation, and 4) starch washing (Eckhoff, 1992a).

The intermediate products are starch, protein and oil. Cornstarch, the primary product yielded by wet milling, may then be further processed into various modified food starches, modified for industrial and paper use, hydrolyzed to produce sweetening products such as high-fructose corn syrup (HFCS), or fermented for ethanol production (Whistler, 1970; Eckhoff, 1992a; White and Pollak, 1995; Paulsen et al., 1996; Troyer and Mascia, 1999). More information on wet milling of maize can be found in Anderson (1970), May (1987), Johnson (1991), and Blanchard (1992).

B. Dry milling

In contrast to wet milling, the objectives of the dry milling process are to separate maize grain into three major parts using mechanical force; endosperm, germ and bran or hull fractions (Brekke, 1970; Alexander, 1987; Pomeranz, 1987; Eckhoff and Paulsen, 1996). The endosperm is processed into grits, meal, and flour, and the germ is processed into oil. The remainder, mainly bran, is used for animal feed. These dry-milled products are used to make cornflakes for breakfast cereals (Fast, 1990), extruded maize snacks, brewed alcoholic beverages, maize meal for snack foods, maize flour for food mixes, bread making and for nonfood products such as gypsum board or plastics (Pomeranz, 1987; Eckhoff, 1992a).

Simplified procedures of the degerminating dry milling process are 1) cleaning, 2) tempering (i.e., adding steam or water to grain and maintaining the moisture content of grain at about 18-24 %), 3) removing the hull (i.e., pericarp, seed coat, aleurone layers) and the germ without affecting the endosperm (Brekke, 1970; Eckhoff and Paulsen, 1996). The various fractions are then sifted, the endosperm milled into grits, and the oil extracted from the germ.

The end products and a range of coarse to fine grits (also called regular grit or 'semolina' (Mestres et al., 1991)), and corn meal or flour, are then dried and the byproducts of hull and germ cake are combined into animal feed (Brekke, 1970; Eckhoff and Paulsen, 1996). The typical yield of products from dry milling are: animal feed, 35%; corn oil, 1%; grits, meal and flour, 60%; the remaining 4% being shrinkage (Brekke, 1970). Further detailed information on dry milling process can be found in Brekke (1970), Alexander (1987), and Pomeranz (1987).

C. Alkaline processing–'masa' production or nixtamalization

Maize alkaline processing produces 'masa', which is fried or baked into tortilla chips, corn chips, or other various snacks and foods (Eckhoff and Paulsen, 1996). This processing method was developed by native Latin Americans and such products are still the major source of energy and nutrition in many Central American countries (Katz et al., 1974; Rooney and Serna-Saldivar, 1987; Eckhoff, 1992a).

For alkaline processing, the grain is cooked at near boiling temperatures (85-100°C) in lime solution (about 1% CaO in water) for a relatively short time (5-50 minute), steeped overnight (for up to 15 hours), and then washed to produce nixtamal (i.e., the cooked and steeped maize containing about 50% moisture on a wet weight basis), which is ground into a soft moist dough called 'masa' (Bedolla and Rooney, 1982; Rooney and Serna-Saldivar, 1987; Serna-Saldivar et al., 1993; Eckhoff and Paulsen, 1996).

Masa is shaped into thin circles or other various shapes and baked into tortilla chips or fried into corn chips (Rooney and Serna-Saldivar, 1987). Tortilla chips have been traditionally consumed by a large group of people in Latin America (Serna-Saldivar et al., 1992) and now consumption is also increasing in the U.S. and other countries (Pollak and White, 1995; Barrett, 1996; Anon, 1998). Bedolla and Rooney (1982), Trejo-Gonzalez (1982), Paredes-Lopez and Saharopulos-Paredes (1983), Rooney and Serna-Saldivar, (1987), and Serna-Saldivar et al. (1990) have extensively reviewed maize tortilla production technology and related works.

2-3-2. Maize quality attributes desired for milling industries

Webster defines quality as an essential character, a degree of excellence, or a distinguishing attribute. In this aspect, maize quality is a nebulous term because its definition depends on the end use (Watson, 1987a; OTA, 1989; Brooker et al., 1992). As already indicated, quality characteristics of maize grain required by each milling industry differ somewhat depending on the process technology and the final products. Generally, the wet milling industry aims at a high yield of starch and it therefore requires soft endosperm maize with a large amount of starch. On the other hand, the dry milling industry and alkaline processing are looking for hard endosperm maize (Eckhoff and Paulsen, 1996; Shandera et al., 1997).

In relation to grade standards, medium hard yellow US No.2 grade dent maize (see also Table 2-2) is most commonly preferred for use by wet and dry millers, largely for economic reasons (White and Pollak, 1995). Maize grade quality factors such as moisture content, percentage of foreign material and damaged grains and mycotoxin levels are always important for all food product industries (Watson, 1987a; Paulsen, 1992). Since current grading factors do not fully describe maize quality attributes for each specific milling industry, other empirical tests are needed to determine the most suitable attributes of maize for each industry (Freeman, 1973; Watson, 1987a; Hill, 1988). In the following section, description of maize quality attributes will focus mainly on the desired physical or mechanical attributes of the grain for each milling industry which are most often cited in the literature.

A. Quality attributes for wet milling (starch production)

The main objective of wet milling is achieving a high yield of starch. Thus first and foremost wet millers desire maize that has a large amount of starch (about 70%) (Eckhoff and Paulsen, 1996). Starch content and starch yield is determined primarily by the genetic background of maize (Zehr et al., 1995) and cultural and environmental conditions under which it is grown (Freeman, 1973).

However high starch content in the grain does not assure high starch recovery or starch yield (Fox et al., 1992). Maize harvested at high moisture content and artificially dried using extremely high drying air temperatures has a reduced starch recovery and quality (Vojnovich et al., 1975; Weller et al., 1988). It is generally recommended that for best results, maize used in wet milling should not be dried over 60°C (Paulsen et al., 1996; Watson, 1987a). High drying temperatures result in starch gelatinization (at 64 to 72°C), protein denaturation (at 55 to 65°C), and loss of endogenous enzyme activity (at 43 to 46°C) (Eckhoff and Tso, 1991; Paulsen et al., 1996). The detrimental effects of excessive drying temperatures not only lower starch recovery but also retard the steeping process because of low solubilization of the heat damaged endosperm protein (Wall et al., 1975; Peplinski et al., 1994; Eckhoff and Paulsen, 1996). Therefore, many wet millers prefer to purchase low-temperature dried or non heat-damaged maize at higher prices (Paulsen et al., 1996).

Stress cracks, which are normally induced by rapid drying at high drying air temperatures (Thompson and Foster, 1963), have been successfully used as an indirect test of degree of protein denaturation and starch gelatinization in maize grains (Paulsen et al., 1996). However, in current U.S. maize grade standards, heat-damaged properties are not included or only refer to grain discoloration (Paulsen et al., 1996). Discoloration occurs above temperatures that induce irreversible biochemical changes of protein and starch in the maize grain (White and Ross, 1972; Peplinski et al., 1994). Thus low stress-cracked maize (less than 20 to 30%) is desirable for high starch recovery and such maize also results in less breakage and less broken material during handling, and therefore has a higher premium value (Paulsen et al., 1996).

The tetrazolium test, warm germination test, and cold test have been used to provide an indication of grain viability and starch recoverability (Eckhoff and Paulsen, 1996). A high viability and a high germination percentage assure minimal protein denaturation and excellent starch recovery (Paulsen et al., 1996).

Wet millers also prefer to use large size grains with low moisture content. Fox et al. (1992) reported that 1,000 grain weights were significantly and positively correlated with starch yield. Variable grain size may cause non-uniform steeping (Eckhoff and Paulsen, 1996). Mechanical damage or severe stress cracking increases broken maize, makes the wet milling process difficult and lowers starch recovery (Vojnovich et al., 1975; Eckhoff and Paulsen, 1996).

For wet milling, bulk density (test weight) is an important indicator because grains that have above 72kg/hl bulk density need a longer steeping duration (Eckhoff and Paulsen, 1996). For efficient wet milling, maize with medium density, about 1.25g/cm^3 at 15% moisture content, is required (Paulsen et al., 1996). Low bulk density, or low densities below these levels, indicate soft (opaque) maize, which can be steeped faster (Fox and Eckhoff, 1993) but is more susceptible to breakage in handling and lowers production rate (Watson, 1988; Eckhoff and Paulsen, 1996; Paulsen et al., 1996).

On the other hand, wet millers find that freshly harvested maize is generally more difficult to process than two- to three-month-old maize. They have experienced an increase in foaming during steeping and a need to re-adjust the mill to accommodate the new maize (Eckhoff and Paulsen, 1996; Singh et al., 1998). This grain age related condition is commonly known as the 'new crop phenomenon' and a similar problem with freshly harvested wheat has been reported (Posner and Deyoe, 1986; Shelke et al., 1992). Eckhoff and Paulsen (1996) stated that the new crop phenomenon is probably caused by increased levels of naturally occurring endogenous proteases shortly after harvest. Usually within two months of harvest the new crop phenomenon disappears due to loss of this enzyme activity (Eckhoff and Paulsen, 1996). Singh et al. (1998) recently reported that starch yields were affected by storage condition but not by storage time. They concluded that the long-term loss in starch yield observed by the wet millers could probably be due to microbial deterioration or blending of lower quality maize with good maize.

Mould-damaged maize and mycotoxin levels are of particular concern in every food production industry including wet milling, dry milling and masa production, for their potential in reduction of yield in each of the end products, and also, far more importantly, for health reasons (Bennett and Anderson, 1978; Romer, 1984; Watson, 1987a, 1988; Eckhoff and Paulsen, 1996; Paulsen et al., 1996). Low levels of mycotoxins are always desirable. For aflatoxin less than 10ppb is desired in USA (Paulsen et al., 1996).

B. Quality attributes for dry milling (grits production)

The specific quality characteristics in maize for dry milling have been emphasized by numerous industry representatives (Wichser, 1961; OTA, 1989; Good and Hill, 1992;) because 1) effective dry milling processing depends on certain physical properties of maize such as grain hardness, 2) primary product uses are in foods where purity is highly important, and 3) the dry milling process has less ability to purify products than does the wet milling process (Watson, 1988).

In contrast to wet milling, the most preferred quality characteristic in maize for dry milling is the hard endosperm type of dent maize with a low percentage of stress cracks (low breakage percentage), which can produce a high yield of large endosperm pieces, or so called low-fat "grits" (OTA, 1989; Eckhoff and Paulsen, 1996; Paulsen et al., 1996).

Generally, the harder the grain, the higher the yield of large flaking grits (Wichser, 1961; Paulsen and Hill, 1985a; Wu and Bergquist, 1991; Wu, 1992; Eckhoff and Paulsen, 1996). Therefore, in many cases, dry millers largely depend on numerous direct- or indirect-hardness tests (see Table 2-5) to predict dry milling performance of maize grain (Wichser, 1961; Manoharkumar et al., 1978; Paulsen and Hill, 1985a; Pomeranz et al., 1985; Louis-Alexandre et al., 1991).

A direct method of assessing maize hardness is the measurement of the ratio of cross-sectioned area of hard (horny) to soft (floury) endosperm (H/S ratio or H/F ratio) (Kirleis et al., 1984; Watson, 1987a, b). The amount of the horny part of the endosperm is an important factor in grit yield. Wichser (1961) stated that grits can be made best from maize containing, as an average, 70% horny and 30% floury endosperm; for the production of corn meal, 45% horny and 55% floury endosperm; and for maximum yield of corn flour, a soft type of maize averaging 20% horny and 80% floury endosperm. Horny endosperm has a lower fat content (about 0.04%) and varies less, while floury endosperm has a higher fat content and varies substantially, from 1.1 to 2.4%. In general, grit yield increases as the proportion of horny endosperm in the grain increases (Brekke, 1970).

Grain hardness is closely related to grain density (Paulsen and Hill, 1985a; Pomeranz et al., 1984). Thus quick but indirect measurements of grain hardness i.e., floaters test (Wichser, 1961; Manoharkumar et al., 1978), true density (Mohsenin, 1970) or bulk density (Paulsen and Hill, 1985a; Watson, 1987a, see also next section 2-4-2, D), have been used. Generally as maize hardness increases, grain density increases, bulk density increases (Dorsey-Redding et al., 1991), and the grain shows a greater resistance to grinding (Pomeranz et al., 1985; Paulsen, 1992; Li et al., 1996).

Maize grain densities range from 1.19 to 1.34g/cm^3 at about 15% moisture content and hard maize typically has densities above 1.27g/cm^3 (Eckhoff and Paulsen, 1996). For dry milling, to obtain a high percentage yield of large flaking grits, maize grain density should range from 1.25 to 1.28g/cm^3 and bulk density range from 73.4 to 75.9kg/hl (Paulsen et al., 1996).

On the other hand, flint maize, having the hardest endosperm character (from 62 to 76% horny endosperm (Watson, 1988)), is less effective for dry milling than hard endosperm dent maize because of its small grain size, round shape, and different moisture diffusion characteristics (Eckhoff and Paulsen, 1996). Dry millers also prefer large grains because larger grains are more effective for producing larger flaking grits (Paulsen et al., 1996) while the smaller grain size results in smaller grits and the round grain shape makes degermination more difficult (OTA, 1989; Eckhoff and Paulsen, 1996).

The drying process is a major concern to maize dry millers since high temperature rapid drying induces stress cracking (Thompson and Foster, 1963; OTA, 1989; Peplinski et al., 1989; Kirleis and Stroshine, 1990). Increases in severely stress-cracked grains make the degermination process difficult and thus lower the yield of quality grits and oil contamination due to insufficient separation between endosperm and germ fractions (Brekke, 1970; Brooker et al., 1992; Eckhoff and Paulsen, 1996).

Dry millers prefer less than 20% of stress-cracked maize grains and such maize lots have an additional premium value from trade markets (Paulsen et al., 1996). However, the optimal drying air temperature for the dry milling of maize has not yet been determined (Brooker et al., 1992), although Peplinski et al. (1982) recommended a maximum drying air temperature of 82°C for maximum grit yield and quality.

Low percentage breakage and low numbers of damaged grains are desirable for dry milling. If high levels of broken- and damaged-maize grains are processed, smaller endosperm pieces or high-fat meal and flour content could be increased (Eckhoff and Paulsen, 1996; Paulsen et al., 1996). Such maize and dry milled products have a low market value and go into animal feeds (Eckhoff and Paulsen, 1996; Paulsen et al., 1996). Dry millers are also sensitive to microbial deterioration of the maize (Watson, 1988; Eckhoff and Paulsen, 1996). Low levels of mycotoxins and moulds are always desirable for dry milling. Allowable aflatoxin levels are less than 10ppb in Japan and 20ppb in the U.S. (Paulsen et al., 1996).

C. Quality attributes for alkaline processing (nixtamalization)

The desirable maize properties for alkaline processing are directly related to the cooking and processing quality of the grain (Serna-Saldivar et al., 1993). Alkaline processing involves cooking and steeping processes at elevated temperatures for some time, and thus some chemical and physical changes (i.e., water uptake, starch gelatinization, and removal of the pericarp) in the maize grains occur during alkaline cooking (personal communication, A. K. Hardacre, 1996). Sufficient water uptake, starch gelatinization and the degree of pericarp removal during nixtamalization are essential for producing good quality masa (Bedolla and Rooney, 1982; Rooney and Serna-Saldivar, 1987). To obtain the optimal hydration and starch gelatinization during nixtamalization, a consistent and uniform hardness and size of the grain is desirable (Jackson et al., 1988; Eckhoff and Paulsen, 1996).

Maize that can be easily processed into high yields of masa usually has excellent dry-milling properties as well (Rooney and Serna-Saldivar, 1987). In general, the properties desired for alkaline processing are uniformly sized dent or flint maize with intermediate to hard endosperm texture, free of damaged grains and stress cracks, an easily removed pericarp, and bright yellow or white colour (Rooney and Serna-Saldivar, 1987; Serna-Saldivar et al., 1990). Variable grain hardness due to blending hybrids or cultural and postharvest management result in non-uniform cooking (Eckhoff and Paulsen, 1996). Some grains (or parts of grains) will be undercooked while others will be overcooked. Anything that can reduce the variability among grains helps to achieve more uniform cooking (Rooney and Serna-Saldivar, 1987).

Hard endosperm maize is most preferred by masa producers because it has more uniform cooking characteristics and is easier to process into a good quality masa than soft endosperm maize (Rooney and Serna-Saldivar, 1987; Eckhoff and Paulsen, 1996). Soft endosperm maize and stress-cracked or broken grain are more easily overcooked during processing and produce a sticky masa, which is not suitable for making tortillas (Bedolla and Rooney, 1982).

Maize with a higher content of stress-cracked and broken or damaged grains also leads to excessive dry matter losses during processing (Jackson et al., 1988; Pflugfelder et al., 1988; Almeida-Domínguez et al., 1998). Considerable variability also exists in ease of pericarp removal between maize hybrids due to differences in hardness of the grain and the infrastructure of the pericarp tissue (Rooney and Serna-Saldivar, 1987; Serna-Saldivar et al., 1991). Residual pericarp is always present in masa but too much pericarp affects the subsequent tortilla processing (Rooney and Serna-Saldivar, 1987; Eckhoff and Paulsen, 1996). Thus masa producers prefer to select maize hybrids that have the ease of pericarp removal characteristic (Eckhoff and Paulsen, 1996).

In addition, the preferred colour of maize for tortillas and corn chips is dependent on regional and local preferences (Rooney and Serna-Saldivar, 1987), but generally bright, clean white and yellow grains are desirable for food maize (Floyd et al., 1995). The cleanest and brightest colour in tortillas can be obtained when the maize has white cobs instead of red or pink cobs (Montemayor and Rubio, 1983; Hahn et al., 1984).

Another detrimental colour in tortilla is called 'brown banding' caused by mites' attacking during grain maturation. The mites cause red bands in the pericarp, which turn brown on alkaline cooking, producing off-coloured products (Rooney and Serna-Saldivar, 1987). In general, the maize used in masa production requires a low level of insect infestation and microbial infection because spoilage in the maize grain reduces its storage life and also the shelf life of the products and decreases product palatability and sanitation (Eckhoff and Paulsen, 1996).

D. Summary

Desirable maize quality attributes differ depending on the end user. However, all industries which use maize grain for raw material for human consumption always emphasize the need for purity and uniformity (i.e., freedom of damage resulting from the machinery and the drying process, free from microbial spoilage, and uniformity in hardness, size, and low breakage). Although controversy about prediction tests and quality measurements for each milling industry still exists, many studies have shown which characteristics of grains are applicable to each. From the literature, the desired properties of maize grains for each form of processing can be summarized as Table 2-1.

Table 2-1. The desired maize quality attributes for milling industries (Serna-Saldivar et al., 1993; Eckhoff and Paulsen, 1996; Paulsen et al., 1996).

Milling Industry	Primary End product	Quality attributes (the desired ranges in test variables)
Wet milling	***Starch***	• Medium hard or soft endosperm, (medium density (about 1.25g/cm^3)) – High starch content (69-70%) and high starch recovery • Low stress cracks (less than 20%) • Low breakage (broken maize; average range at 8-12% or less) • Low drying air temperature (lower than 60^{o}C) • High viability (Tetrazolium; more than 85%) • Large grain size (1,000-grain weight; 270-350g) • Low mycotoxin (Aflatoxin; less than 10 ppb)
Dry milling	***Grits***	• Hard endosperm (high H/S ratio (70% hard and 30% soft) or high bulk density (73.4 to 75.9 kg/hl) or high density (1.25-1.28g/cm^3)) • Low stress cracks (less than 20%) • Low breakage (less than 10%) • Large grain size (1,000-grain weight; 270-350g) • Low mycotoxin (Aflatoxin; less than 10 ppb in Japan and 20 ppb in the US)
Alkaline processing	***Masa***	• Hard endosperm (high bulk density (77.2kg/hl) or high density (by nitrogen-displacement pycnometry >1.3g/cm^3)) • Low stress cracks (less than 20%) • Large grain size (1,000-grain weight; more than 300g) • Easier pericarp removal, bright white or yellow colour • Low mycotoxin (Aflatoxin; less than 10 ppb)

2-4. Measurement of maize grain quality

2-4-1. Importance of grain standards and quality measurement in marketing

A. The role of grain standards in grain production and marketing

In the previous sections, the quality of maize grain was defined and explained from the end users' point of view. The specific demands by the end-users require maize producers and grain handlers to use the 'quality of maize grain' in marketing for better prices (Watson, 1987a). This interaction between the end users, producers, and handlers in relation to quality attributes in maize grain has also impacted on governments in maize producing countries to provide and revise grain standards, and on plant breeders to develop and release new varieties (Watson, 1987a; OTA, 1989). Figure 2-4 shows a triad that forms in the production and marketing system with respect to quality characteristics in maize (OTA, 1989).

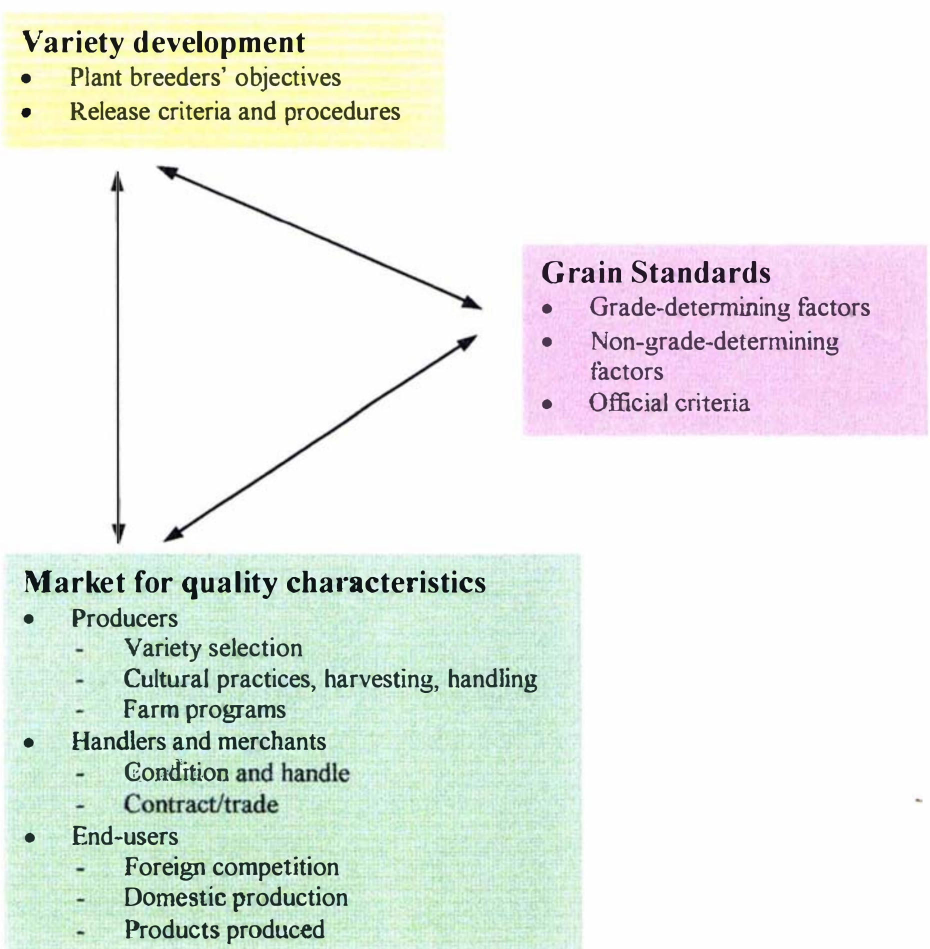


Figure 2-4. A triad among the components of the interdependent grain system (Source: Office of Technology Assessment (OTA), 1989).

Each of the three double-headed arrows in Figure 2-4 implies an impact on quality as well as on the triad system. Firstly, the required quality characteristics are influenced by the end-users' needs for the products produced and by foreign competition. Producers make agronomic decisions e.g., variety selection, cultural practice, and farm programs, in response to these incentives, and handlers and merchants handle and condition grain to meet contract specification. The incentives established in the market by the interaction between the end-users, producers, and handlers generate the triad system and reflect on the grain standards that can provide a useful description to enhance marketing, and also influence variety development and release by the plant breeders. Revisions in grain standards by governments and new varieties released by plant breeders again impact on producers, handlers, and end users to interact with each other for enhancing grain quality (OTA, 1989).

Through the loop of this triad system, more accurate and effective measurement of important characteristics e.g., variety identification, certain intrinsic quality, and grading factors, play an important role in creating other incentives to every interdependent triad-system component for enhancing quality (Watson, 1987a; OTA, 1989). Because the main tool by which quality information is transmitted throughout the system is grain standards, incentives and disincentives cannot be established unless accurate, consistent, and timely information on measurement of important quality characteristics that can incorporate the objectives of grain standards is provided in the market (OTA, 1989).

B. The purpose of grain standards and grade determination of maize grain

Description of numerical grades of grain is an essential means of communication between buyers and sellers and it also creates incentives for producers to supply uniform and consistent quality grain in the market channel (OTA, 1989). In the US, a country which produces a major part of maize grain exports to other countries, grain grades and standards were established early in 1916 by the Federal Grain Inspection Service (FGIS) (Albert, 1975; Hoffman and Hill, 1976; Watson, 1987a). Following some changes over the years, the purposes of the US grain standards had evolved by 1986 to introduce economic principles into the criteria for setting numerical factor limits and for selecting the factors to be included (Hill, 1988; OTA, 1989). The four objectives of the US grain standards are: 1) to define uniform and accepted descriptive terms to facilitate trade; 2) to provide information to aid in determining grain storability; 3) to offer end-users the best possible information from which to determine end-product yield and quality; and 4) to create tools for the market to establish incentives for quality improvement (Hill, 1988; OTA, 1989; Eckhoff and Paulsen, 1996).

Currently, the grading standards for maize in the US (Table 2-2) are based on selected physical attributes of whole grains. These attributes were chosen to define and measure grain properties in a relatively simple way to differentiate among lots of maize differing in quality (Watson, 1987a). These grading factors are: 1) test weight (a measure of bulk density), 2) broken corn and foreign material (BCFM), 3) heat-damaged grains and 4) total damaged grains (Watson, 1987a; Eckhoff and Paulsen, 1996). As indicated in Table 2-2, these four factors determine grades of maize numerically from 1 to 5. A lower grade, known as 'Sample Grade', is that in which any objectionable odour, certain weed seeds, or other foreign substances are detected (Watson, 1987a; Eckhoff and Paulsen, 1996).

Table 2-2. Grading standards for maize grain in the US (Watson, 1987a; Eckhoff and Paulsen, 1996).

		Maximum Limits		
			Damaged grains	
Grade	Minimum Test Weight per Bushel (lb)	Broken Corn and Foreign Material (%)	Heat-Damaged Grains (%)	Total (%)
US No.1	56.0	2.0	0.1	3.0
US No.2	54.0	3.0	0.2	5.0
US No.3	52.0	4.0	0.5	7.0
US No.4	49.0	5.0	1.0	10.0
US No.5	46.0	7.0	3.0	15.0
US Sample Grade†	-	-	-	-

† US Sample grade is maize that:

a) Does not meet the requirements for the grades US No. 1-5; or
b) Contains eight or more stones which have an aggregate weight in excess of 0.20% of the sample weight, two or more pieces of glass, three or more crotalaria seeds (*Crotalaria* spp.), two or more castor beans (*Ricinus communis* L.), four or more particles of an unknown foreign substance(s) or a commonly recognized harmful or toxic substance(s), eight or more cockleburs (*Xanthium* spp.) or similar seeds singly or in combination, or animal filth in excess of 0.20% in 1000g; or
c) Has a musty, sour, or commercially objectionable foreign odour; or
d) Is heating or otherwise of distinctly low quality.

The lowest of any of these four factors determines the maximum grade given (Eckhoff and Paulsen, 1996). For example, if BCFM, total damage, and heat damage of a lot of yellow maize are all below the No.1 grade level of 2, 3, and 0.1%, respectively, but bulk density is 53 lb/bu (68.2 kg/hl), the maize is graded US No.3Y (Watson, 1987a). Before September 1985, moisture was also a grade-determining factor in US, but it is now only a standard, the value of which must be shown on the invoice (Watson, 1987a).

C. Measuring grading factors and accuracy of grade determination

As described above, four factors, test weight, BCFM, heat-damaged grains, and total damaged grains, are measured for determining maize grade in the US. Test weight is a measure of bulk density obtained by weighing a specific volume of the grain. In the US test weight or bulk density is measured in pounds per bushel (lb/bu; 1bu= 0.03524m^3, 0.3524hl), while in other countries it is measured with the metric system in kilograms per hectoliter (kg/hl) (Watson, 1987a; Brooker et al., 1992).

The BCFM is the percentage of fine maize particles and other material that will pass through a 4.76-mm round-hole sieve plus all matter other than maize such as small pieces of cob or stalk, that remain on top of the sieve after sieving (Eckhoff and Paulsen, 1996).

Heat damaged grains represent the percentage of maize grains by weight that are materially discoloured and damaged due to any excessive heat source (Watson, 1987a; Eckhoff and Paulsen, 1996). Total damaged grains include heat-damaged grains and damage due to mould invasion (Eckhoff and Paulsen, 1996). The term, 'damaged grains' for US grade standards indicates grains and pieces of maize grains that are heat-damaged, sprouted, frosted, badly ground-damaged, mouldy, diseased, or otherwise materially damaged (Watson, 1987a). Heat-damage in this sense is normally detected by visible observation, which is discoloration of the entire grain due to heat generated by excessive microbial growth in an unfavorable storage condition (Watson, 1987a; Eckhoff and Paulsen, 1996).

The 'otherwise materially damaged' category includes insect-bored grains and damage caused by excessive temperature during artificial drying including grains that are discoloured, wrinkled, blistered, puffed, swollen, or obviously crazed or stress cracked (Watson, 1987a).

In these measurements of grading factors, the accuracy of the result depends on the sample size, sampling method, and measurement techniques. Parker et al (1982), Manis (1992) and Clarke and Orchard (1994) have provided detail about sampling procedure and sampling equipment. Grain samples are obtained by either on-line or stationary methods. On-line sampling can be done manually, using an 'Ellis cup' or a 'pelican sampler', or mechanically, using a 'diverter-type mechanical sampler'. Stationary sampling is usually performed with a grain probe. Many researchers have recommended multiple-probe sampling rather than a one-time probing sample for stationary sampling to reduce variation and increase representativeness (Lai, 1978; Watson, 1987a; OTA, 1989). In the US the inspection grading of maize uses 1,000g of 'work sample', which represents the often very large maize lot (Watson, 1987a). Since the US maize grade system requires a very low level of detection in some grade-determining characteristics such as heat damage (0.1 or 0.2% for US No.1 or No.2) or aflatoxin content (20 parts per billion (ppb)), the work sample size and sampling accuracy have often been controversial (Johnson et al., 1969; Elam and Hill, 1977; Hurburgh and Bern, 1983).

From the sampling and measurement procedures, the results of inspection grading of maize thus possess two types of variation: random and nonrandom. Random variation is natural and unavoidable. Nonrandom variation occurs from 1) uneven distribution of grain or impurities, 2) improper sampling procedures, and 3) inaccurate measurement (Watson, 1987a). Any methods and types of sampling which can reduce nonrandom errors are helpful in increasing the accuracy of the grading results (OTA, 1989).

Among nonrandom variation, uneven distribution in a load of grain is more of a problem with some characteristics such as BCFM and differing moisture content in lots of maize than with others. Other nonrandom errors involve inaccurate measurements from incorrectly calibrated and maintained instruments, or from analysts not following correct procedures. This problem is now being helped by the introduction of automated measurement of bulk density, BCFM, and moisture, which are used with a computer to calculate and record results (Watson, 1987a). However, some subjective tests, which include damage, odours, other grain, weed seeds, and foreign objects, are still very difficult to automate (Watson, 1987a).

D. Limitations in national grain grades and standards and fair average quality (FAQ) for export trade contracts

The basic function of numerical grain grades and standards is to allow buyer and seller to be able to agree on a price, using a universal set of rules that both accept and understand for grain marketing for consistent and uniform quality (Watson, 1987a; Hill, 1988; OTA, 1989). With this respect, the US maize grades and standards are not a universal or international standard. Maize grades and standards differ from country to country (e.g., Table 2-3 and 2-4) (Watson, 1987a; Brooker et al., 1992; Eckhoff and Paulsen, 1996). However, the US grain standards provide a background for other major maize exporting countries, such as, Argentina, South Africa and China, which have many similarities (Eckhoff and Paulsen, 1996; Watson, 1987a).

For example, Argentina and South Africa use a different size and shape of sieve to separate broken maize (Table 2-3 and 2-4) (Argentines use a 3.17-mm (8/64-inch) triangular-hole sieve) and use different terminology (South Africans use 6.35-mm (16/64-inch) round-hole sieve for separating 'defective maize grains' that combine broken maize with mould damaged grains), but both countries agree with the US in using the lowest factor for grade determination and using the same definition of damaged grains (Watson, 1987a; Brooker et al., 1992).

Table 2-3. Argentine grading standards for maize (Paulsen and Hill, 1985b; Watson, 1987a; Eckhoff and Paulsen, 1996).

	Maximum allowable percentages			
Grade	Damaged grains† (%)	Broken grains‡ (%)	Foreign material (%)	Minimum bulk density (kg/hl)
1	3	2	1	75
2	5	3	1.5	72
3	8	5	2	69
4*	12	9	2	-

*Grade 4 is added only in years when damage levels exceed Grade 3.
†Fermented, mouldy, sprouted, etc.
‡Pieces of grains that will pass through a 3.17-mm triangular-hole sieve.

Table 2-4. South Africa grading standards for yellow maize (Watson, 1987a; Eckhoff and Paulsen, 1996).

	Maximum allowable percentages (%)			
Grade	Defective grains*	Foreign material	Other-coloured grains	Collective Deviations†
1	9	0.30	2	7
2	20	0.50	5	13
3	30	0.75	5	25

*Grains showing mould, insect damage, or mechanical damage, plus pieces of grains that will pass through a 6.35-mm round-hole sieve.
†Collective deviations where the value given represents the maximum sum of defective grains, foreign material, and other-coloured grains allowed for that grade.

Because of these differences in grain grades between countries, internationally, many nations have been selling and buying grains under the 'fair average quality' (FAQ) system (Watson, 1987a; Brooker et al., 1992; Clarke and Orchard, 1994). The contract for the FAQ system specifies that the quality of grain at the port of destination shall be equal to the monthly average of all the grain received at that port from a particular country of origin (OTA, 1989; Brooker et al., 1992). The destination FAQ thus gives an advantage to buyers and a disadvantage to sellers.

However, since the FAQ simply describes whatever quality is produced and is flexible by changing crop year, the FAQ contract does not cover all factors on which buyers might like information, and the floating standard leaves the buyer uncertain as to what quality may be received for processing (OTA, 1989). Therefore the FAQ system provides no incentive for improving quality. In recent years the FAQ contract for maize grains has been less frequently used. Argentina, South Africa, and Brazil all report exporting maize grain primarily on numerical grades in each country. However, European buyers have reported continued use of destination FAQ on soybean (OTA, 1989).

2-4-2. Measurement techniques for maize grain quality

A. Scope

Information about maize quality has been accumulated for many years by numerous researchers (Watson, 1987a). However, some controversial criteria for current grading factors still exist because of the mechanical or viscoelastic behavior (hardness) of the maize grain (Watson, 1987a and b; Mestres et al., 1995; Li et al., 1996), and variation in grain sampling and testing equipment (Parker et al., 1982; Hurburgh and Bern, 1983; Watson, 1987a; Clarke and Orchard, 1994). In the following sections, measurement of several important physical and mechanical characteristics of maize grain will be presented, including moisture content, hardness, density (true density and bulk density), breakage susceptibility, and stress cracking.

B. Moisture content

Moisture content is an important characteristic that has a significant influence on maize quality during harvest and postharvest handling (Watson, 1987a). Moisture content is also economically important. The level of moisture in maize grain often determines market price, primarily due to the cost of drying to safe storage levels and due to 'shrinkage', which refers to the loss in weight after drying (Watson, 1987a; Nelson, 1994). Thus, determination of moisture content is critical and a standard method has been developed for uniformity (AACC, 1983; Anon., 1990a and 1992). Moisture content, i.e., the quantity of water held by grain, is usually expressed on a percentage basis as mass of water per unit mass of wet grain (wet-weight basis), or as mass of water per unit mass of dry grain (dry-weight basis) as follows (Hunt and Pixton, 1974; Brooker et al., 1992):

$$\text{MC (wet-weight basis)} = \left(\frac{\text{mass of water}}{\text{mass of wet grain}} \right) \bullet 100 \quad \text{------------------------} \quad (2.1)$$

$$\text{MC (dry-weight basis)} = \left(\frac{\text{mass of water}}{\text{mass of dry grain}} \right) \bullet 100 \quad \text{------------------------} \quad (2.2)$$

where, MC is moisture content and the mass of dry grain is the mass of the wet grain minus the mass of moisture in the sample (Brooker et al., 1992). A wet basis moisture content is convertible to a dry basis, and vice versa, using the formula presented by Brook (1992) and Brooker et al., (1992). In trade and industry the moisture content on a wet-weight basis is most often used, while in scientific terms the moisture content on a dry-weight basis is preferred (Hunt and Pixton, 1974).

An accurate measurement of true moisture content in cereal grains is difficult because moisture or water is ubiquitous and an integral part of grain constituents (Watson, 1987a). Grains contain water in three different forms: 1) absorbed water (free water), loosely held by capillary attraction in the intercellular spaces; 2) adsorbed water (bound water), held more firmly by molecular attraction; and 3) water of constitution, part of the chemical structure (Hunt and Pixton, 1974; Watson, 1987a; Henderson, 1991). Methods of measuring the moisture content in cereal grains theoretically remove and determine the absorbed and adsorbed water from the grain but not the water of constituent (Henderson, 1991).

Methods for moisture measurement in cereal grains are of three general types: 1) fundamental or basic reference methods; 2) practical reference methods; and 3) rapid empirical methods for commercial measurements (Waston, 1987a). Among them, the most accurate method for determining the moisture content of grains is a fundamental or basic reference method that consists of extraction of the water chemically and calculation of the amount stoichiometrically (Brooker et al., 1992). As one of the basic reference methods, the Karl Fisher (KF) method (Hart and Neustadt, 1957) is used to determine the absolute moisture in the sample, which is removed by alcohol extraction (Eckhoff and Paulsen, 1996). The Karl Fisher method, which is considered the standard for measuring grain moisture, however, is seldom used because it is time-consuming and complicated in practice.

For the practical reference methods, oven drying is usually used. Watson (1987a), Henderson (1991), and Manis (1992) summarized the oven methods for determination of moisture content of maize. The standard method for maize in US is the AACC Air Oven Method (Now Method No. 44-15A) which uses a 103 ± 1°C oven for 72 hours (Anon., 1990a, 1992; Eckhoff and Paulsen, 1996). In this method, fifteen grams of unground sample are dried in opened aluminum containers. After drying, the containers are removed, lidded and placed in a desiccator to cool to room temperature (Eckhoff and Paulsen, 1996). Most European countries, however, have accepted a method known as the ICC oven method (ICC-101/1), which was proposed by the International Association for Cereal Chemistry (IACC) as an international standard method (Watson, 1987a). In this method, maize is ground to a specific particle size and then dried for 4 hours at 130°C in an air oven. The repeatability of this method is between 0.05% and 0.1% (Eckhoff and Paulsen, 1996). Although these oven methods are used for determining maize grain moisture for standards, several sources of variation exist within the methods such as grinding, temperature, humidity ratio of the air in the oven (Balascio et al., 1989), properties of grain, drying containers, time of drying, and sampling (Hunt and Pixton, 1974; Henderson, 1991). Hunt and Pixton (1974), Henderson (1991) and Christensen et al. (1992) reviewed those error terms in measuring moisture content in cereal grains with oven methods. Recent research by numerous scientists has shown that the US standard method records moisture at about 0.7-0.8% lower than the best available basic methods such as the KF method (Watson, 1987a; Eckhoff and Paulsen, 1996) and the results of the ICC oven method show a 0.7% moisture content difference with the US standard method (AACC-44-15A) (Watson, 1987a).

On the other hand, for rapid, empirical and practical methods of moisture measurement, 'electronic' dielectric moisture meters are most widely used in commerce because of their speed and simplicity of operation, and relatively low cost (Watson, 1987a). This measurement is based on differences in dielectric properties of grain samples differing in moisture content (Nelson, 1981, 1994). The most widely used electronic meters in the US are Motomco 919 (also in Canada), Steinlite S5250, Burrows 700, and Dickey-john GAC series (Watson, 1987a; Eckhoff and Paulsen, 1996). However, the accuracy and precision of measurement using these meters is poorer than for the other methods, especially above 25% moisture content (Watson, 1987a). Paulsen et al. (1983a) and Hurburgh et al. (1985) reported differences between commercial moisture meters and air-oven readings, and within moisture meters of up to ± 3.0%, especially in high moisture content grain (above 23-24%). Their results forced legislation requiring re-calibration of all meters used in the grain trade (Watson, 1987a).

Other practical methods of measuring grain moisture content include wide-line nuclear magnetic resonance (NMR), near-infrared (NIR), non-destructive radio-frequency (RF) and microwave measurement (Watson, 1987a; Nelson, 1994). The NMR and NIR instruments are expensive and complicated compared with the dielectric meters, but the NIR instruments are now becoming widely used in commerce because of the need to quickly measure protein content and other grain components along with moisture (Watson, 1987a). Recently, RF and microwave methods for measuring moisture content of cereal grains have been extensively researched and the results showed positive feasibility for non-destructive and on-line practical application (Nelson et al., 1990; Kraszewski and Nelson, 1994; Nelson, 1994; Nelson et al., 1998; Kraszewski et al., 1998 and 1999).

C. Hardness

Maize quality has become under careful scrutiny in the past decade for two main reasons. First, commercial handling of grain induces grain breakage, which increases losses, costs of aeration and removal of fines that cause increased microbial spoilage and risks of fires and explosions (Watson et al., 1993; Mestres et al., 1995). Second, maize processors have specific demands to ensure higher yield of end products. Hardness of maize grain is therefore regarded as one of the most important intrinsic quality factors to measure for prediction of processing quality and grain performance during postharvest handling and storage (Watson, 1987a).

Despite the importance of maize grain hardness as a measure of quality, there is no general agreement on the definition of hardness in terms of fundamental physical units (Jindal and Mohsenin, 1978; Mestres et al., 1995). Because maize grain is viscoelastic in nature and heterogeneous in structure, its mechanical properties (i.e., hardness) change with time, temperature, moisture content, chemical composition, and microstructure within the grain (Li et al., 1996, Dombrink-Kurtzman and Knutson, 1997). For these reasons it is difficult to measure maize hardness using a uniform and fundamental unit. Numerous studies have used various methods for measuring hardness of maize grain. Table 2-5 summarizes several measurement techniques for mechanical properties of maize grain including hardness, density and breakage.

A quantitative method of maize hardness is the measurement of the ratio of cross-sectioned area of hard (horny) to soft (floury) endosperm (H/S ratio or H/F ratio) (Kirleis et al., 1984; Watson, 1987a, b; Louis-Alexandre et al., 1991). This visual observation technique for determining grain hardness is time consuming and subject to a large coefficient of variability (Watson, 1987a; Li et al., 1996). As alternative methods, several researchers have proposed various 'impact tests' that determine static and dynamic hardness of individual grains using specific compression and impact forces (Jindal and Mohsenin, 1978; Loesch et al., 1977; Tran et al., 1981; Lawton and Faubion, 1989). These methods are more objective than quantitative measurement and more reliable in predicting milling quality, but the results show moisture dependent variation, especially at high moisture content. The methods are also time-consuming and not practical for routine measurements (Watson, 1987a; Mestres et al., 1995; Li et al., 1996).

In comparison with the above quantitative methods and impact tests, grinding methods such as the Stenvert hardness test (SHT) are faster and more practical for determining grain hardness (Table 2-5). In the SHT, a micro-hammer-mill (Glen Creston type) is used to grind 20g of maize at a speed of 3,600-rpm (Stenvert, 1974; Pomeranz et al., 1985).

The measurement parameters in SHT are: 1) the grinding resistance time (sec); 2) the height of the column (mm); and 3) the volume or weight ratio of coarse to fine particles from sieving the ground material (Pomeranz et al., 1985) or 4) grinding energy (Li et al., 1996). Pomeranz et al. (1984) also reported high correlation between density, average particle size (APS) and near-infrared reflectance at 1.680-μm value of the ground maize and they suggested that density, NIR, and APS can be used for routine testing in maize hardness determination.

However Pomeranz et al. (1984) concluded that these hardness determinations can be interpreted properly only if the history of the grain (i.e., drying and postharvest handling) is considered. Because breakage susceptibility and hardness are related and affect utilization of maize, both must be considered in its evaluation (Watson, 1987a). More importantly, as with breakage susceptibility, hardness measurements are highly sensitive to moisture content of the grains (Herum and Blaisdell, 1981; Tran et al., 1981; Pomeranz et al., 1986b). Below 16% moisture content, maize grains show lower resistance to grinding and correlation coefficients among and between hardness and breakage susceptibility parameters were much higher for the 12% than for the 16% moisture maize (Pomeranz et al., 1986b).

Table 2-5. Summary of techniques for measuring mechanical properties of maize grains.

Techniques	Methods and efficiency	Units
Hardness measurements: 1) Quantitative methods	• ***Method;*** using 20-30 maize grains, measure the ratio of cross-sectioned area of hard and soft endosperm under visual inspection by eye (Hamilton et al., 1951; Paulsen et al., 1983b; Kirleis et al., 1984) or machine (Gunasekaran et al., 1988; Louis-Alexandre et al., 1991; Mestres et al., 1991;) • ***Efficiency;*** Subjective and time-consuming	H/S ratio or Vitreousness index (VI) (%)
2) Impact tests	• ***Methods;*** measuring static and dynamic hardness by using compression and impact tests including, - Barley pearler (Taylor et al., 1939, Tran et al., 1981) - Instron compression (Jindal et al., 1978; Tran et al., 1981) - Pendulum impact tester (Srivastava et al., 1976; Jindal and Mohsenin, 1978) - Kramer shear press (Loesch et al., 1977) - Tangential abrasive dehulling device (TADD) (Oomah et al., 1981; Reichert, et al., 1986; Lawton and Faubion, 1989) etc. • ***Efficiency;*** 1) more objective than quantitative methods, 2) reliable for predicting milling quality, 3) moisture dependent variables, 4) time-consuming, not practical	N (Newton) or Pascal – N/m^2, kg/cm^2, or lb/ft^2
3) Grinding methods	• ***Methods;*** - Stenvert hardness test (SHT) – grinding 20g of maize with a specific microhammer mill (Stenvert, 1974) and measure; 1) the grinding resistance time, 2) the height of column of ground maize and 3) the volume and weight ratio of coarse vs. fine (Pomeranz et al., 1985), or 4) the grinding energy (Li et al., 1996) to a certain volume (17ml) at a specific moisture content - The ground particle size by using specific sieving-average particle size (APS) (Pomeranz et al., 1984) - NIR reflectance at a specific range- 1.680µm, 2.230 µm for maize and wheat, respectively (Pomeranz et al., 1985, 1986a, and 1986b; Osborne, 1991) • ***Efficiency;*** Rapid, practical and the most reliable for predicting milling properties	Grinding time (sec), The height of column of ground maize (mm), The ratio of coarse vs. fine (volume and weight), or Grinding energy (J), NIR (1.680-µm) or APS (µm)
Density measurements	• ***Methods;*** Bulk density, True density (Mohsenin, 1970), or Floaters test (Wischer, 1961) • ***Efficiency;*** rapid and simple but in some cases, not reliable for prediction of milling properties (e.g., maize dried at extreme high temperatures)	True density; (g/cm^3) Bulk density; (lb/bu, kg/hl)
Breakage measurements	• ***Methods:*** testing the mechanical breakage or brittleness of maize using impact forces. The most widely used devices are: - Stein breakage tester (SBT) (Miller et al., 1979, 1981a, and 1981b; Watson et al., 1986) - Wisconsin breakage tester (WBT) (Singh and Finner, 1983) - Modified Stein breakage tester (MSBT) or Ohio breakage tester (OBT) (Watson and Keener ,1993; Watson et al., 1993) • ***Efficiency;*** reliable predictions of mechanical behavior of maize grain for postharvest handling and drying, but highly sensitive to sample moisture	Percentage (%) of broken maize passing through a specific sieve (4.76-mm (12/64 inch) round-hole sieve in US)

Thus for comparative hardness measurements, maize samples should be carefully adjusted to equal moisture levels (usually in the range of 11-14%) or a moisture correction factor applied to the results (Watson, 1987a). Herum and Blaisdell (1981) reported that temperature effects are smaller than that of moisture content, but maize becomes slightly more brittle as temperature is lowered from 38 to 4°C.

For quick but indirect methods of determining maize grain hardness, density measurements (Pomeranz et al., 1984; Paulsen and Hill, 1985a) such as the floaters test (Wichser, 1961), true density (Mohsenin, 1970) or bulk density (Paulsen and Hill, 1985a; Watson, 1987a) have been used (Table 2-5). However, these indirect measures of grain hardness such as floaters and grain density may not adequately reflect grain corneous vs. floury endosperm status under a wide range of cultural management conditions (Bauer and Carter, 1986) and are not useful for maize grains that have been dried at extremely high temperatures (Watson, 1987a).

D. Density - bulk density and true density

Density of maize is an indication of hardness and of maturity (Watson, 1987a). It is measured in two ways: bulk density (test weight) or true density of individual grains (In this text, the term, 'test weight' is used as a synonym for 'bulk density') (Eckhoff and Paulsen, 1996).

The bulk density of maize has been included as a factor of the US grain standards and is important for storing and transporting maize because it determines the size of container required for a given lot of maize (Watson, 1987a; Brooker et al., 1992). Bulk density is also used in maize processing industries as an important indicator of processing yield and the quality of the final products (Watson, 1987a). However, consistent relationships between bulk density value and favorable end-use properties have not been established (Brooker et al., 1992; Manis, 1992).

Currently, bulk density is determined using a special apparatus, which is described by Hoseney and Faubion (1992) and Manis (1992). The bulk density is affected by many factors, such as moisture content, drying conditions, grain damage, and environmental conditions during grain maturity (Hall, 1972; Hall and Hill, 1974; Watson, 1987a) and importantly it is hybrid dependent (Hardacre et al., 1997). Thus comparisons of bulk density as an indication of quality can only be made within the same hybrid and hybrids with inherently lower average bulk densities are not necessarily of poor quality (Hardacre et al., 1997; Brenton-Rule et al., 1998). In general, a high bulk density value in a maize hybrid is especially favorable to dry millers for high value of prime grits (Paulsen and Hill, 1985a; Stroshine et al., 1986), while hybrids with a low bulk density value may be suitable for the wet milling or animal feed industries (Hardacre et al., 1997).

True grain density, which more accurately represents maize hardness characteristics, is usually expressed as specific gravity (g/cm^3) and is determined by using an alcohol (ethanol) or toluene solution displacement of a pre-weighed 100g maize sample (Watson, 1987a; Eckhoff and Paulsen, 1996). The mass of the maize divided by the volume displaced by the 100g of maize represents the true density. Another method for determining true density is to use a helium-air displacement pycnometer that also provides data on porosity or inter-seed space (Thompson and Isaacs, 1967; Gustafson and Hall, 1970). It is a convenient, nondestructive method but requires a 200g sample (Watson, 1987a). With these methods, true density of maize ranges from about 1.19 to $1.34 g/cm^3$ at about 15% moisture content (Eckhoff and Paulsen, 1996). Maize with densities above average ($1.27 g/cm^3$) is generally considered as hard maize (Paulsen, 1992; Eckhoff and Paulsen, 1996).

Another useful method of comparing densities is the 'flotation test' or 'floaters test' in which 100 grains are placed in a 1.275 specific gravity solution of sodium nitrate or other suitable chemicals (e.g., a mixture of deodorized kerosene and tetrachloroethylene) and the number floating is determined (Watson, 1987a; Eckhoff and Paulsen, 1996). The higher the percentage of floating grains, the softer the maize. The percentage of floaters is also compared to a chart, which can provide a reading of relative hardness of maize grain especially for dry milling characteristics which accounts for variation due to grain moisture content (Wichser, 1961; Watson, 1987a). This method, however, is not useful with maize that has been dried at excessive temperatures because large internal void spaces tend to distort the results (Watson, 1987a).

All the density tests mentioned above are affected by grain moisture content (Nelson, 1980; Dorsey-Redding et al., 1990) due to a lower density of water than the grain (Watson, 1987a). Density tests must be made on maize samples of uniform moisture content or a moisture correction factor must be developed (Watson, 1987a). For a standard adjustment of moisture content for bulk density of maize grain in New Zealand, 14% moisture content is suggested and bulk density can be adjusted using the following formula (Hardacre et al., 1997):

Bulk Density (BD) at 14% = BD of grain + (0.3 x (MC_a-14)) ------------------------- (2.3)

Where, MC_a is the moisture content (MC) of the maize sample at the time of testing. For example, if a grain sample at 23% MC has a BD reading of 70.0 kg/hl, its corrected BD at 14% MC will be 72.7kg/hl, i.e., assuming for every 1% decrease in moisture there will be a 0.3kg/hl increase in bulk density (Hardacre et al., 1997).

E. Breakage susceptibility

With grain hardness measurements, another important aspect of measuring mechanical properties of maize grain is breakage susceptibility, which is defined in the US as the potential for grain fragmentation when subjected to impact forces during handling or transport (AACC, 1983; Anon., 1990b). Increasing breakage in maize grain caused by various impacts during machine harvesting and subsequent handling increases broken grain and fine material through the marketing system and lowers the value of maize (Keller et al., 1972; Paulsen and Nave, 1980; Pierce and Hanna, 1985; Paulsen et al., 1989a; Pierce et al., 1991; Watson et al., 1993).

Because of the importance of breakage, a number of breakage testers that can measure maize breakage under simulated handling conditions have been developed. Table 2-5 shows the most widely used breakage testers in the US. Among them, the Stein breakage tester model CK-2M (SBT) has historically been recommended as the standard device for measuring the breakage susceptibility of maize grain (AACC, 1983). In the SBT test, a 100g pre-sieved sample of grain is placed in a steel cylinder (9-cm-diameter) and impacted using an impeller rotating at 1790 rpm for 2 minutes. The sample is then removed and screened using a 4.76-mm (12/64 inch) round hole sieve. The percent breakage is then expressed using the following formula (equation 2.4):

$$\text{Breakage (\%)} = \frac{\text{(Original weight – weight retained by 4.76mm-round-hole sieve)}}{\text{Original weight}} \bullet 100 \qquad \text{------------------------------ (2.4)}$$

Another major breakage tester, a centrifugal impacting device for measuring grain breakage susceptibility was developed by Singh and Finner (1983) at the University of Wisconsin (Wisconsin breakage tester (WBT)). In the WBT test, 200 g of pre-sieved maize sample is impacted against a vertical wall using an impeller rotating at 1800 rpm. On the basis of precision, rapid throughput, sturdy design, and rotor uniqueness, the WBT was once suggested as a standard device replacing the SBT (Watson and Herum, 1986). But it was later rejected by Watson and Keener (1993) and Watson et al. (1993) for the Modified Stein Breakage Tester (MSBT), a partially automated SBT, which was designed by an Ohio agricultural research team and has also been called the Ohio breakage tester (OBT). Several benefits from using the MSBT in comparison with an original type of SBT that were described by the authors are: 1) reducing grinding time from 2 minutes to 30 sec and reducing total time for determining breakage susceptibility from 7-8 minutes to 3.5-4 minutes, 2) reducing manual operational error by automating the discharge of impacted maize, 3) increasing grain sample from 100g to 200g, and 4) greater precision in results with smaller standard deviations than the original SBT.

Although the SBT has been used as a standard device for measuring breakage for maize grain, the effect of the breakage testers, the SBT and the WBT, on maize has been controversial for two main reasons: 1) testing impacts differ with device type and 2) breakage susceptibility is affected by several physical characteristics (Watson, 1987a; Eckhoff and Paulsen, 1996). The Stein breakage testers primarily abrade away at the surface of the grain, so soft endosperm maize tends to have higher breakage than hard endosperm (Kirleis and Stroshine, 1990) and thus breakage from Stein testers appears as fine pieces of grains and as powder. The Wisconsin tester provides one large impact, so hard endosperm maize tends to shatter more easily and breakage will appear as large pieces of grains (Eckhoff and Paulsen, 1996). Consequently, the SBT has greater correlation with maize hardness characteristics, while the WBT has better correlation with stress cracks and grain size and shape (Martin et al., 1987; Kirleis and Stroshine, 1990; Weller et al., 1990).

Other researchers have reported more reliable correlations between the SBT and stress cracks and also reported more reliable predictions for breakage during handling (Gunasekaran and Paulsen, 1985; Pomeranz et al., 1986b; Watson and Herum, 1986; Eckhoff, 1992b). This conflicting information in breakage susceptibility as measured with the SBT and the WBT is due largely to the moisture content of the maize sample and to a lesser extent, sample temperatures (Herum and Blaisdell, 1981; Paulsen, 1983; Watson et al., 1993; Eckhoff and Paulsen, 1996). The effects of drying and hybrid on breakage susceptibility have also been reported extensively by many researchers, and these are reviewed in the following sections.

F. Physical damage and stress cracks

Watson (1987a) reviewed physical damages in maize grain during modern-postharvest handling. He divided them into two types of damage: 1) exterior and 2) interior. Both External and internal damage in grains lower maize grade and processing quality. Such damaged grains are more susceptible to breakage during subsequent handling and also more vulnerable to mould during storage (Pierce and Hanna, 1985; Pierce et al., 1991; Ng et al., 1998c).

Exterior damage includes visible and some non-visible damage, which is caused by mechanical impact from machinery at harvest or attacks from birds or insects in the field during grain development (Foster, 1975; Herum, 1987; Watson, 1987a; Eckhoff and Paulsen, 1996). This mechanical damage can be determined by visual examination of each grain categorizing grains into some form of class of damage levels, or by using a numerical damage index (Watson, 1987a).

The internal type of damage, termed 'stress cracks', which are tiny cracks or fissures formed inside a grain, are caused by excessive compressive or tensile stresses occurring during or after drying, cooling or rehydration (Thompson and Foster, 1963; Sarwar and Kunze, 1989; Brooker et al., 1992) or due to impact from high-velocity loading (Moreira et al., 1981). Consequently, measurement of the extent of stress cracks in grains is one of the subjective methods for measuring breakage susceptibility (Miller et al., 1981b) and also an indicator of heat damage such as starch gelnatinization and protein denaturation (Eckhoff and Paulsen, 1996; Paulsen et al., 1996). Although stress cracking itself does not inflict direct physical damage to maize grains, maize lots with high stress crack levels are more susceptible to breakage during subsequent handling (Watson, 1987a; Gunasekaran and Muthukumarappan, 1993). Furthermore, such grains lower the yield of large flaking grits in dry milling and reduce starch recovery in the wet milling process (Eckhoff and Paulsen, 1996). Stress cracks are determined by candling 50-100 whole grains individually over a light source. A grain is held with the germ side over the light and stress cracks are visually inspected (Thompson and Foster, 1963; Eckhoff and Paulsen, 1996). Stress cracks can also be observed by low-power X-ray (Escasinas, 1986; Kudra et al., 1994), laser optical methods (Gunasekaran, 1985) and a scanning electron microscope technique (Balastreire et al., 1982; Gunasekaran et al., 1985). More recently, automated inspection of stress cracks and mechanical damages in maize grains has been explored using machine vision systems (Gunasekaran et al., 1987; Casady and Paulsen, 1989; Paulsen et al., 1989b; Kim, 1991; Liao et al., 1994; Han et al., 1996; Ng et al., 1998a and 1998b), and magnetic resonance imaging (MRI) (Ruan et al., 1992; Song et al., 1992; Song and Litchfield, 1994).

2-5. Maintenance of maize grain quality

2-5-1. Agronomic factors affecting maize grain quality

A. Scope

Recent work on maize grain quality has been focused on breakage susceptibility and hardness, as they are closely related to milling quality (Bauer and Carter, 1986; Kniep and Mason, 1989; Shandera et al., 1997). Grain breakage susceptibility and hardness differ with maize hybrids (Johnson and Russell, 1982; Paulsen et al., 1983b) and these physical attributes are affected by agronomic management factors such as soil nitrogen level, plant density, sowing date, and water regime (Bauer and Carter, 1986; Weller et al., 1990; Ahmadi et al., 1995). In this section the effect of hybrid and soil nitrogen level on physical attributes of maize grain (e.g., breakage susceptibility and hardness) will be discussed.

B. Hybrid – yield vs. quality

Traditionally, the maize breeders' primary concern has been to increase grain yield. Grain quality has been a secondary consideration (OTA, 1989; Wrigley and Morris, 1996). More recently, however, the diversification of grain markets and introduction of modern agricultural management systems have increased the importance of maize grain quality, and the strategy of maize breeding programmes is now to improve grain quality prior to grain yield (OTA, 1989). At present, maize breeding focuses on identifying new, widely adapted hybrids that increase farmer's profit with 1) high yield, 2) efficiency of harvest, and 3) improved end-use characteristics (Troyer and Mascia, 1999).

Improvements of maize breeding skills and cultural management systems have continuously increased grain yield since 1900 (Cardwell, 1982; Duvick, 1992; Tollenaar and Dwyer, 1999). In early maize breeding, maize breeders focused on improving physiological traits of maize plants such as ear height, lodging and cold tolerance, and adaptability to high plant density for maximum productivity (Duvick, 1992). They paid little attention to physical quality attributes (e.g., breakage susceptibility) of grains because maize was harvested with ear-pickers and naturally dried on the farm, and thus maize grain had little damage and breakage was low (OTA, 1989). In recent decades, increasing market diversification and the introduction of modern agricultural management systems have brought quality considerations into maize breeding and production (OTA, 1989; Troyer and Mascia, 1999). Modern technology for grain harvesting and postharvest handling (e.g., machine harvesting, artificial drying) increases maize production efficiency, but it often causes harvest loss and grain damage (Foster, 1975; Herum, 1987). Combine harvesters allow the harvesting of maize earlier, but grain moisture content is still high and artificial drying is required. Most farmers dry grain rapidly using high-temperature dryers, but this excessively rapid removal of moisture causes stress cracking in maize grains (Thompson and Foster, 1963). If such grains move through market channels, the grains break easily, fine material is increased and the value of the end products will be lowered (Hansen et al., 1994).

Therefore hybrids with low grain breakage (e.g., harder starch or flintier types) and which were easier to combine harvest became an advantage to farmers. Studies have shown that maize grains with: 1) small size (LeFord and Russell, 1985; Miller et al., 1981b), 2) flat shape (Martin et al., 1987), 3) high grain weight (Bauer and Carter, 1986; Moes and Vyn, 1988), 4) high density (LeFord and Russell, 1985), and 5) high bulk density (Bauer and Carter, 1986; Moes and Vyn, 1988) are less susceptible to breakage. Most of these grain characteristics of maize hybrids which are related to breakage susceptibility are highly heritable (Johnson and Russell, 1982; LeFord and Russell, 1985) and thus proper selection of hybrids can reduce breakage susceptibility and improve physical attributes of maize grain for a specific end use such as dry milling (Paulsen et al., 1983b; Vyn and Moes, 1988; Weller et al., 1990).

On the other hand, maize hybrids that dried faster in the field and in the dryer became more desirable as fuel costs rose (Troyer and Ambrose, 1971; Cross, 1995). Conventional maize breeding has recently been aimed at achieving hybrids that have a lower harvest moisture content for reducing breakage susceptibility (Hameed et al., 1994b; Cross, 1995) because hybrids that dry rapidly in the field produce grains with higher bulk density, reduced risks from frost or unfavorable weather for harvest and also reduced postharvest drying costs and damage (Cross and Kabir, 1989; Cross, 1995). Sweeney et al. (1994) and Cross (1995) reviewed several factors related to lowering harvest moisture content in maize grain. These factors are: 1) husk looseness and senescence rates (Troyer and Ambrose, 1971; Baron and Daynard, 1984; Sweeney et al., 1994), 2) ear size and ear moisture at physiological maturity (Cross et al., 1987; Cross and Kabir, 1989; Brooking, 1990), 3) pericarp thickness (Purdy and Crane, 1967; Baron and Daynard, 1984), and 4) rate of grain filling (Kang et al., 1986; Kang and Zuber, 1989; Newton and Eagles, 1991).

Maize breeders, however, have encountered difficulties in finding hybrids that have satisfied all the advantageous categories mentioned above (i.e., low breakage and fast dry-down rate) in a single hybrid or a genotype (Cross, 1995). For example, the hybrid B73 x Mo17, a popular, high yielding dent maize hybrid in the US corn-belt, has a fast dry-down rate, but is susceptible to breakage (Stroshine et al., 1986). On the other hand, hybrids with low breakage susceptibility do not assure high yield, fast dry-down rate, or disease resistance (Paulsen et al., 1983b; Bauer and Carter, 1986; Stroshine et al., 1986). An alternative selection is by using tropical germplasm such as 'Cateto' inbred lines (Goodman and Brown, 1988; Hameed et al., 1994a and 1994b). Lowering harvest moisture content and increasing bulk density achieved by introducing Cateto flint maize into US corn-belt dent maize reduced breakage susceptibility (Hill et al., 1989; Hameed et al., 1994b).

A similar effort in New Zealand has been undertaken (Eagles and Hardacre, 1985; Eagles and Lothrop, 1994). For a cool, temperate environment, the main objective of maize breeding programmes in New Zealand was initially to improve cool season adaptability of elite corn-belt dent maize inbred lines or hybrids (Eagles and Hardacre, 1985). In recent years, this programme has successfully developed cold-tolerant local hybrids using early maturing highland maize from Central Mexico germplasm (Eagles and Hardacre, 1990; Eagles and Lothrop, 1994). More recently the maize breeding programme in New Zealand has added improvement of milling quality to keep up with increasing demand for maize for human consumption (Anon, 1995). The efforts for improving grain quality include 1) developing standard grain quality assessments for New Zealand (Hardacre et al., 1997; Brenton-Rule et al., 1998) and 2) field trials of commercial maize hybrids for testing local adaptability (Brenton-Rule et al., 1996; Hardacre and Pyke, 1998b).

Although developing better hybrids for high yield and high quality is useful, obtaining desirable specific end use quality attributes of maize grains must be linked with suitable cultural management and postharvest handling (OTA, 1989). The interaction between environment (e.g., temperature, rainfall and insects) vs. maize hybrid and cultural management (e.g., fertilizer, plant density, sowing date, and drying methods) vs. maize hybrid largely affects agronomic performance and physical attributes of maize grain (Johnson and Russell, 1982; OTA, 1989; Hameed et al., 1994b).

Therefore grain quality assessment in association with field trial results is crucial for a better understanding of the potential marketability of hybrids currently in commercial use, because such information can be helpful to both the end users' and farmers' decision making on hybrid choice (Brenton-Rule et al., 1996). For example, the results of field trials of several commercial hybrids in New Zealand indicated different grain quality attributes and local adaptability. Brenton-Rule et al. (1996) found that some hybrids (P3753, P3730, P3514, and Raissa) have potential for use in the dry milling industry at both low (89,000 plants/ha) and high (110, 000 plants/ha) plant densities due to their larger portion of hard endosperm, and other hybrids (DK626, P3751, DK471) are suitable for wet milling or feed industries due to their soft endosperm characteristics. On the other hand, Pioneer brand hybrids 'P3394' and 'P3514' from US, which have hard endosperm characteristics (i.e., high bulk density), have potential for the dry milling industry, but both are late maturing hybrids and inappropriate to cool season areas such as the Manawatu region of New Zealand (Brenton-Rule et al., 1996).

C. Nitrogen – quality vs. cost

While the potential for improving maize quality through genetics is high, selection of a good hybrid does not assure the production of desirable maize quality because several cultural management factors significantly influence maize quality attributes (Bauer and Carter, 1986; Ahmadi et al., 1995). One of the most important cultural practices related to maize quality is the use of nitrogen fertilizer.

Traditionally, most farmers have considered nitrogen application for increasing maize yield (Sinclair, 1998), not for improving grain quality. Recent increases in the food use of grain has restored maize producers' attention to the effect of nitrogen on maize quality, especially grain hardness and breakage susceptibility (Bauer and Carter, 1986; Kniep and Mason, 1989; Sabata and Mason, 1992; Ahmadi et al., 1995; Patwary, 1995; Oikeh et al., 1998).

Grain hardness (vitreousness) increases as soil fertility increases (Hamilton et al., 1951; Tsai et al., 1992; Kettlewell, 1996). That is where nitrogen is limiting, higher soil nitrogen produces a larger proportion of hard endosperm (i.e., a high horny to floury endosperm ratio) in maize grain than lower soil nitrogen (Hamilton et al., 1951, Bauer and Carter, 1986; Ahmadi et al., 1995). Hamilton et al. (1951) and Ahmadi (1991) also reported a positive relationship between nitrogen concentration and grain hardness and between grain protein (zein) content and grain hardness. They concluded that higher soil nitrogen rates increased overall grain hardness due to increased nitrogen concentration in the grain, and apparently reduced breakage susceptibility in most hybrids.

Because of these effects of nitrogen on grain hardness and breakage susceptibility, soil nitrogen level is now regarded as a more important variable to consider for grain breakage than hybrid selection (Sabata and Mason, 1992). However, hardness and bulk density of maize grains are inconsistent with increasing nitrogen levels among locations and among years within the same hybrid (Bauer and Carter, 1986; Sabata and Mason, 1992; Oikeh et al., 1998). This interaction between hybrid and environmental condition makes it difficult to suggest a general recommendation of the nitrogen level to achieve desirable physical quality attributes for a specific end use such as dry milling (Sabata and Mason, 1992; Oikeh et al., 1998).

Nevertheless, Oikeh et al. (1998) recommended use of 30-60 kg nitrogen per hectare (N/ha) for maize dry milling in the West African moist savanna, when using flintier maize hybrids. But, nitrogen level is relatively low compared to conventional use for maximum yield in the US corn-belt and in New Zealand. In New Zealand, an average rate of about 100-150 kg nitrogen per hectare has been recommended for maximum yield (Steele, 1983 and 1985; Underwood, 1985; Stone et al., 1998). Recently, Patwary (1995) investigated the effect of side dressing nitrogen level on dry milling characteristics (hardness) of three dent maize hybrids in a cool season area (Manawatu) in New Zealand. He found that nitrogen fertilizer application at 115 kg N/ha (250 kg Urea/ha) maximized grain yield, but better dry milling quality (i.e., higher grain protein content, bulk density, and hardness) was recorded at 230 kg N/ha (500 kg Urea/ha). This result agreed with previous reports from the US corn-belt (Bauer and Carter, 1986; Kniep and Mason, 1989; Sabata and Mason, 1992).

On the other hand, the use of nitrogen is expensive and it has been also noted that the rate of nitrogen for optimum economic return is often lower than the rate for maximum yield. Stone et al. (1998) recommended use of relatively low amount of nitrogen (at about 50 to 100 kg N/ha depending on soil nitrogen status) for the highest economic return. When farmers use relatively low nitrogen rates, they must consider selection of a maize hybrid with high yielding potential and high nitrogen use efficiency (Sabata and Mason, 1992). Studies have shown that nitrogen use efficiency (i.e., grain production per unit nitrogen (N) available in the soil (kg grain /kg N) (Moll et al., 1982)) differs with maize hybrid (Tsai et al., 1992; Ahmadi et al., 1993; Czyzewicz and Below, 1994; Balconi et al., 1998). For example, Tsai et al. (1992) reported three different hybrid groups that required different levels of nitrogen for maximum grain yield, low (134 kg N/ha), intermediate (134 to 201 kg N/ha) and high (201 kg N/ha), respectively. They found high-nitrogen responsive hybrids (e.g., B73 x Mo17) decreased nitrogen use efficiency as nitrogen level increased, but nitrogen use efficiency was static for low nitrogen-responsive hybrids (e.g., P3732). However they found that low nitrogen levels generally reduced grain vitreousness (hardness) in all maize hybrids.

Most of the nitrogen absorbed by maize plants is nitrate (NO_3^-) and the nitrate is then reduced into proteins and other cellular constituents (Blevins, 1989; Salisbury and Ross, 1992). Thus any factors that can affect absorption of NO_3^- or nitrogen metabolism can influence grain hardness and brittleness as a result of changing protein content in maize grains (Reed et al., 1980; Crawford et al., 1982; Salisbury and Ross, 1992). Particularly during grain filling, temperature (Jones et al., 1981; Hunter et al., 1977) and plant moisture status (Harder et al., 1982; Pierre et al., 1977) influence starch and protein assimilation in maize endosperm. Frost before physiological maturity is thought to make grain brittle and more susceptible to handling damage (Benson, 1984; Watson, 1987a).

D. Other factors

Several cultural practices (e.g., plant density, sowing date) and environmental factors (e.g., soil moisture, frost) can also significantly affect grain hardness and breakage susceptibility (Bauer and Carter, 1986; Moes and Vyn, 1988; Shumway et al., 1992). Delayed sowing, high plant densities, and severe water stress often cause low yield and poor quality of maize. These conditions increase stress and increase competition for nutrients and water, causing grain to become soft and brittle at harvest (Watson, 1987a; OTA, 1989).

Bauer and Carter (1986) reported that regardless of maize maturity, average grain breakage susceptibility increased about 1.5 to 2.0% for each 2.0 plants per m^2 increase in plant density within an average range of plant density of 1.75, 3.75, 5.75, and 7.75 plants per m^2. They also found that delayed sowing increased breakage susceptibility of grain. These results are similar to other reports (Cloninger et al., 1975; Moes and Vyn, 1988; Vyn and Moes, 1988; Kniep and Mason, 1989; Shumway et al., 1992). However there have been no consistent reports from the literature about the relationship between water availability and physical attributes of maize grain. Some authors reported that irrigation increased grain breakage susceptibility (Bauer and Carter, 1986), but others found irrigation increased grain density and lowered breakage susceptibility (Sabata and Mason, 1992; Shumway et al., 1992).

On the other hand, most authors have experienced year to year and region to region variation in grain hardness and breakage susceptibility in the same maize hybrid with the same level of each of the above cultural practices (i.e., plant density, sowing date, nitrogen, and irrigation). They have explained that this is mainly due to variation from the environment (e.g., soil, climate) and with drying method (Bauer and Carter, 1986; Ahmadi et al., 1993; Mannino and Girardin, 1994; Oikeh et al., 1998).

While climatic variation is often unpredictable and basically beyond human control, drying method is controllable, and the effect of drying on grain quality is predominant (Thompson and Foster, 1963; Watson, 1987a; OTA; 1989). In the following section, the importance of drying and the effect of drying on maize quality traits will be discussed.

2-5-2. Postharvest drying and maize quality

A. Importance of maize grain drying

Although hybrid selection and cultural practice can improve maize quality, high quality can not be guaranteed if grains are not properly harvested and handled after harvesting. In modern agriculture especially, drying is the most important process for maintaining maize quality after harvesting (OTA, 1989; Brooker et al., 1992).

The primary function of grain drying is to reduce moisture content to a level safe for storage. More recently two other factors: 1) energy use and efficiency and 2) grain quality (Hukill, 1947; Meiering et al., 1977; Pierce and Thompson, 1981; Sokhansanj, 1984; Gunasekaran and Gempesaw, 1987; Zhang and Litchfield, 1991; Bakker-Arkema et al., 1996; Bern, 1998) have had to be considered. In the US, drying requires about 60% of the total energy used in maize production (Figure 2-5) and the process of drying has a greater influence on breakage susceptibility than any other grain handling operation (OTA, 1989; Brooker et al., 1992).

If the drying process is not properly controlled, internal grain fissures, so called stress cracks, are prevalent, and make the grain more susceptible to breakage (Thompson and Foster, 1963). Increasing grain breakage susceptibility due to improperly controlled drying results in an increase in broken maize and fine material during subsequent handling, and finally lowers the maize grades or milling quality (Watson, 1987a).

In the following section, the effect of drying method on maize quality, especially breakage susceptibility and stress cracking will be discussed.

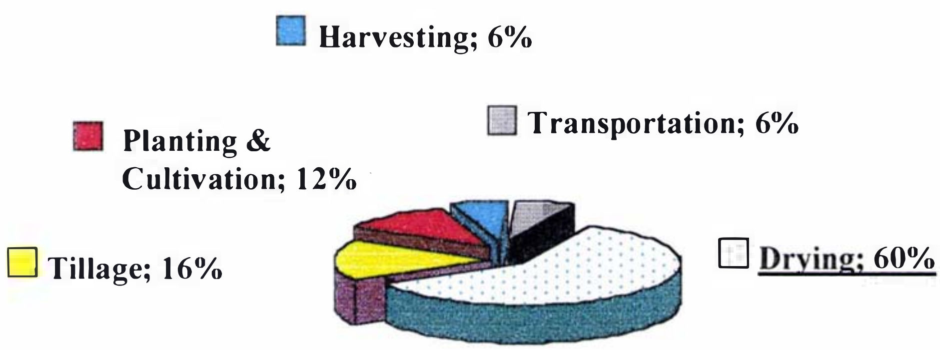


Figure 2-5. Energy requirements for production of maize in the Midwestern United States as a percentage of the total (Brooker et al., 1992).

B. Modern artificial drying methods and maize grain quality

Natural sun drying or low-temperature drying usually has little effect on maize quality attributes such as stress cracking, density, breakage susceptibility or germination. However, rapid drying with high temperatures can cause grain damage (e.g., loss of germinability, discoloration, stress cracking) and lower maize quality (e.g., high breakage susceptibility) (Hardacre and Pyke, 1998a). Traditionally, maize cobs were harvested and dried and stored with simple methods such as sun drying or natural air ventilation in a crib (Picard and Proctor, 1994; Trim and Robinson, 1994). In recent decades, the combine harvester made drying by natural means obsolete, and artificial drying has largely replaced natural drying methods in most maize production countries (Brook, 1992; Trim and Robinson, 1994; Champ et al., 1996).

For artificial drying, various types of dryers have been developed and used. The variation in dryer types and designs has developed because of 1) drying capacity (i.e., varying amounts of grain to be dried), 2) energy efficiency (i.e., the acceptable cost of equipment and management), or 3) grain quality (i.e., the potential effect of the drying process on the quality of the grain) (Brook, 1992). Most grain dryers are developed, however, basically on the same principles or use for the same functions for drying: 1) airflow (to remove moisture from the grain being dried) and 2) heat (to change the temperature of the air and the grain, to change the amount of water the air can hold, and to increase the rate of moisture flow from the grain) (Brook, 1992).

The artificial drying used to dry grains can be divided into two broad groups by drying air temperature levels: 1) low temperature drying and 2) high temperature drying (Brooker et al., 1992). The low temperature drying system or low temperature dryers use either unheated air or air heated to raise its temperature by up to 6°C (10°F) or less. The high temperature drying system or high temperature dryers normally use drying air temperature from 50°C (120°F) to 300°C (570°F), depending on the dryer type and the required grain quality (Brooker et al., 1992).

In this review, however, classification of the drying methods in two broad groups: on-farm drying (i.e., drying grains in the farm location) and off-farm drying (i.e., drying grains commercially) is presented.

On-farm drying (In-bin drying)

In many cases, both low and high temperature drying occur in the bin and the process is referred to as 'in-bin drying' or 'in-store drying'. In-bin drying forms the majority of modern artificial drying systems in farm locations (i.e., on-farm drying) (Loewer et al., 1994; Bakker-Arkema et al., 1996; Driscoll and Srzednicki, 1996).

Low temperature or natural air drying of maize grain with an in-bin drying system requires relatively low initial investment, low cost for management and can produce an excellent grain quality (e.g., minimum stress cracking, see Table 2-6) when operated properly (Loewer et al., 1994). But, farmers do not prefer to use low temperature in-bin drying for maize grain (Hansen et al., 1996) because, when using this drying method, 1) harvesting is often delayed until grain moisture content levels are relatively low (18%

wet basis or less), and 2) low capacity, slow drying can lead to grain spoilage before safe storage levels (14 to 15% wet basis) are reached (OTA, 1989; Loewer et al., 1994). Drying small grains such as wheat and paddy with this low temperature in-bin drying is desirable because those grains are harvested at substantially lower moisture content levels than maize (OTA, 1989; Brook, 1992; Driscoll and Srzednicki, 1996).

As maize is usually harvested at 20 to 30% moisture content levels, maize grain is frequently dried with high temperature drying (OTA, 1989; Hansen et al., 1996). The high temperature drying methods with in-bin drying includes 'batch-in-bin' drying, 'in-bin counter-flow' drying or 'combination drying' (i.e., dryeration) (Brooker et al., 1992; Loewer et al., 1994; Liu et al., 1998).

Batch-in-bin drying uses drying temperatures ranging normally from 35 to 70°C (100-160°F) to dry batches of grain within a bin (Brook, 1992; Brooker et al., 1992). Two types of batch-in-bin drying systems are used; the grain is dried on a perforated floor at the bottom of the bin (i.e., 'on-floor bin-batch' drying) or near the bin roof (i.e., 'roof bin-batch' drying) (Brooker et al., 1992). Compared with other drying systems, high temperature batch-in-bin drying systems require moderate initial investment and often cost less per unit of drying capacity (Gunasekaran and Gempesaw, 1987; Brook, 1992) and thus many farmers still use these methods for maize grain drying (Hansen et al., 1996). But, batch-in-bin drying methods need more labour and produce poorer maize quality (i.e., a low grain viability and bulk density and high percentage of stress cracked grains and breakage) due to over drying and moisture variation across the drying bed (Gustafson et al., 1978; Brown et al., 1979; OTA, 1989; Brook, 1992; Brooker et al., 1992; Loewer et al., 1994).

Another high temperature drying in-bin drying process is called 'in-bin counter-flow drying' because the grain is moving downward and the drying air is moving upward (Brooker et al., 1992, see Figure 2-6). In in-bin counter-flow drying methods, dried, hot grain is semi-continuously unloaded using a sensor-controlled sweep auger from the bottom of the drying bin to storage bins equipped for slow cooling or tempering (i.e. delayed cooling). This system can reduce heat damage and can use relatively high temperatures (70-80°C (160-180°F)) (Brook, 1992; Brooker et al., 1992).

Specially modified in-bin counter-flow drying, designed to reduce brittleness of maize, is called 'dryeration' (Thompson and Foster, 1969; Foster, 1973). In the dryeration process, high temperature drying is stopped when the grain moisture is about two to three percent higher (17 to 18%) than the desired final moisture level and the hot grain is then transferred to the tempering bin, where it tempers from 4 to 12 hours at certain elevated temperatures (ranging from 50 to 70^{o}C) before it is cooled slowly by ventilation with natural air to the final moisture content (Brooker et al., 1992).

Another modification of high temperature drying is called 'combination drying' or 'two stage drying'. In combination drying, grain is initially dried in a high-temperature dryer (e.g., batch-in-bin or counter-flow drying) to an intermediate moisture content of 21 to 22 % and then moved into an second stage in-bin natural or low temperature drying, where it is dried to a safe moisture content level of 13 or 14% (Brooker et al., 1992). This delayed cooling process, tempering or slow cooling relieves stress in the outer layer of grain and dramatically reduces stress cracking and grain breakage (Emam et al., 1979; Gustafson et al., 1983; Sarwar et al., 1989; Brooker et al., 1992, see also Table 2-6).

Table 2-6. Effect of drying method on stress cracking and breakage susceptibility of dried maize grain (Foster, 1973; Brook, 1992).

Drying Method†	**Sound grains without stress cracks (%)**	**Breakage**‡ **(%)**
Conventional continuous flow	8.8	11.3
Dryeration	60.6	6.7
Partial heat or combination drying	82.2	3.9
Unheated air	93.3	1.6

†Tests of the first two drying methods were conducted in 1964 with maize at 25% initial moisture content. The other two methods were tested in 1968 using 23%-moisture content maize for the partial heat or combination drying and 20%-moisture content maize in the unheated air drying. Drying air temperatures used in the combination drying tests were 10°C higher than the average in the other heated air drying tests. Data are averages of three tests for each of the first two drying methods and eight tests for the last two methods listed.

‡Breakage was determined in a sample breakage tester and is defined as broken parts of grains that passed through a 4.76-mm round-hole screen.

Both modified high temperature in-bin drying, dryeration and combination drying have improved energy efficiency, drying capacity, and grain quality compared to conventional batch-in-bin drying (Brook, 1992; Brooker et al., 1992). Especially, the effect of dryeration and combination drying has long been noted for the excellent improvement in maize quality, reducing stress cracking and breakage (Thompson and Foster, 1969; Foster, 1973).

However, these drying methods are still not popularly used on the farm because of the high initial investment and management cost due to the extra equipment needed, such as a tempering bin and fan-heater units for cooling (Brooker et al., 1992; Loewer et al., 1994; Hansen et al., 1996).

Off-farm drying (Continuous flow dryers)

Using air and grain movement through the grain dryer, the grain dryers can be divided into two groups: 1) stationary and 2) continuous (Sokhansanj, 1984). In stationary types, piles of grain of various depths in bins are exposed from the bottom to heated or unheated air (e.g., in-bin drying) while, in continuous types, grain moves continuously through the dryer (Sokhansanj, 1984; Brooker et al., 1992). These continuous flow dryers are high capacity, high temperature dryers, popularly used in the commercial grain industry (i.e., off farm drying) for handling a large amount of grain in the major grain-producing countries (Bakker-Arkema et al., 1996; Liu et al., 1998). In the US more than half of the maize grain produced is now dried commercially with these conventional high-temperature 'continuous flow dryers' (Hansen et al., 1996).

Depending on direction of the grain and air movement through the dryer, the continuous flow dryers are classified as cross-flow, concurrent-flow, mixed-flow or counter-flow (Sokhansanj, 1984; Brooker et al., 1992). Figure 2-6 shows the patterns of grain- and air-movement in the four major types of high-temperature continuous flow dryers. The air and grain move in perpendicular directions in cross-flow dryers, in parallel directions in concurrent-flow dryers, and in opposite directions in counter-flow dryers. The flow of the air and grain in mixed-flow dryers is a combination of cross-flow, concurrent-flow, and counter-flow (Brooker at al., 1992; Bakker-Arkema et al., 1996, see also Figure 2-6).

In principle, the variation in moisture content and temperature, and thus in grain quality, in a sample of dried grain is substantial in cross-flow dryers (Zhang and Litchfield, 1991, see Table 2-7), is less in mixed-flow dryers and is minimal in concurrent-flow or counter-flow dryers (Liu et al., 1998, see Table 2-8).

Among the continuous flow dryers, cross-flow dryers are the most popular dryer types in North America; elsewhere in the world, the mixed-flow dryer is more common (Brooker et al., 1992). However, in a conventional cross-flow dryer, uneven drying and over heating due to the perpendicular direction of the grain- and air-flow, which cause increases in stress cracking and breakage susceptibility in maize grain, have been of concern (Gustafson et al., 1981; Zhang and Litchfield, 1991; Brooker et al., 1992). For example, Table 2-7 shows that the overheated maize grain near the inlet side of the columns in the conventional cross-flow dryer has greatly increased in breakage susceptibility compared with the remaining grain in the column.

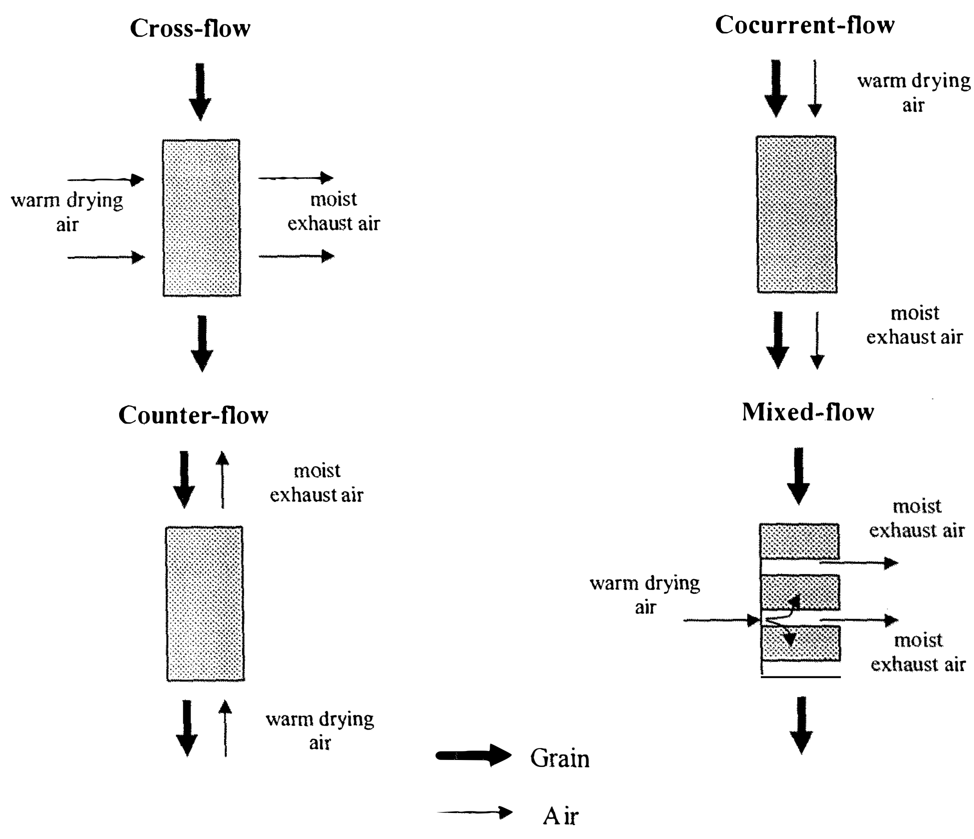


Figure 2-6. Schematics of the four major types of high temperature grain dryers: cross-flow, concurrent-flow, mixed-flow or counter-flow (Bakker-Arkema et al., 1996).

Table 2-7. Grain temperature, moisture content, and breakage susceptibility at different locations in the grain column of a cross-flow dryer after drying maize grain without cooling from 25.5% moisture to an average of 19% at 110°C (Gustafson et al., 1981; Brooker et al., 1992).

Distance from air inlet (cm)	Grain Temperature (°C)	Moisture content (%)	Breakage susceptibility (%)
1.25	102	10	48
7.50	78	20	11
13.75	51	24	10

On the other hand, of the three major types of continuous flow dryers, concurrent-flow dryers cause the smallest increase in the number of stress cracks in maize grains and lowest breakage susceptibility while cross-flow dryers generate the largest increase in stress cracking. Concurrent-flow dryers which are relatively new and superior in uniformity of the drying process, use ultra high drying-air temperatures (200-285°C), but the wet grain is subjected to the hot drying air not for hours (cross-flow dryers), or minutes (mixed-flow dryers), but only seconds (Bakker-Arkema et al., 1996). Thus, the grain does not approach the temperature of the drying air as it does in other types and breakage susceptibility in a concurrent-flow dryer is half that of mixed-flow and one-fourth that of cross-flow dried maize (Table 2-8).

Table 2-8. The average effect of conventional high-temperature dryer type on the drying-air temperature, the maximum grain temperature, the percentage of stress-cracked grains and the breakage of maize grain (OTA, 1989; Bakker-Arkema et al., 1996; Liu et al., 1996).

Dryer Type	Drying air temperature (°C)	Maximum grain temperature (°C)	Stress crack (%)	Breakage (%)
Cross-flow	80-110	80-100	70-85	20
Mixed-flow	100-130	70-100	40-55	10
Concurrent-flow	200-285	60-80	30-45	5

In commercial maize drying, mixed-flow and concurrent-flow dryers are recommended for food use because they produce grains with superior quality characteristics, but their high technology, general misunderstanding of their use and relatively high initial cost has prevented them becoming popular commercially (Bakker-Arkema et al., 1996). The modern cross-flow dryers are less expensive than mixed-flow and concurrent-flow dryers and suitable for drying maize for feed use (Bakker-Arkema et al., 1996).

The recent use of mathematical modelling and computer simulation, such as thin layer drying models, which can be routinely used for analyzing the performance of dryers has improved grain dryers in commercial use, especially the energy efficiency and grain quality of continuous flow dryers (Thompson et al., 1968; Sokhansanj, 1984; Parry, 1985; Nellist, 1987; Weres and Jayas, 1994; Bakker-Arkema et al., 1996). The development of modern cross-flow dryers with air recycling, grain tempering, and grain inverting has improved grain quality characteristics and dryer energy efficiency (Pierce and Thompson, 1981; Gustafson et al., 1983; Bakker-Arkema et al., 1996). Drying maize grain for food use with the modern cross-flow dryer is thus feasible, using lower temperatures (60-75°C) and with air recycling, tempering or installing a grain exchanger (also called a grain inverter) (Brooker et al., 1992; Bakker-Arkema et al., 1996). More detailed information on the drying principle (models), operating methods, economics of use and illustrations of artificial drying, both on-farm (in-bin drying) and off-farm (continuous flow dryers) dryers can be found in McLean (1989), Brook (1992), Brooker et al. (1992), Loewer et al. (1994), and Bakker-Arkema et al. (1996).

As seen in Table 2-9, the artificial drying methods for maize grain mentioned in this section are summarized. Many farmers and grain handlers still use cheaper high temperature dryers, or drying systems such as batch-in-bin drying (on-farm) or conventional cross-flow dryers (off-farm). This results in poor grain quality characteristics, particularly a high percentage of stress cracking and breakage (Bakker-Arkema et al., 1996; Hansen et al., 1996). This may largely be due to economic reasons, including low incentives to farmers and grain handlers because of the relatively low price of maize in the market, no additional premium for high quality (Gunasekaran and Gempesaw, 1987), or less profitability operating an expensive, high quality dryer (Bakker-Arkema et al., 1996).

Table 2-9. Summary of maize grain drying methods.

Dryer location	Drying temperature	Method of drying	Initial Investment	Dried grain quality	Frequency of use
On-farm drying **(In-bin drying)**	Low	Ambient/low-temperature drying	Low	High	Low
	High	Batch-in-bin drying	Low	Low	High
	High-Low	Combination drying (Dryeration)	High	High	Low
Off-farm drying **(Continuous flow)**	High	Cross-flow	Low	Low	High
	High	Mixed-flow	High	Medium	Low
	High	Concurrent-flow	High	High	Low

On top of that, several other factors significantly affect artificial drying performance, such as initial moisture content of the grain, hybrid differences, and dryer operating factors including the human factor and the accuracy of auxiliary equipment (e.g., moisture meter, air temperature meter and the dryer controller) (OTA, 1989). Although recent innovations in grain drying have increased energy use efficiency and quality, the operation of most dryers to produce a high quality output is still incompatible due to these variables. In particular the effect of drying air temperature on maize quality is controversial. In the following section, the effect of dryer operation and drying parameters, especially initial grain moisture content, hybrid and drying temperature, on maize quality will be further discussed.

C. The effect of dryer operation and drying parameters on maize grain quality

a) Dryer operation – the human factor and auxiliary equipment

In many off-farm dryers and on-farm drying models, dryer control is manual, and over-drying frequently occurs (Bakker-Arkema et al., 1996). Grain drying is a complicated heat and mass transfer process of a heat-sensitive biological product and is often not well understood by the average dryer operator (OTA, 1989; Loewer et al., 1994). Especially in commercial drying (off-farm drying), grain drying is a seasonal job which requires 12-hours per day, 7 days a week, for two to three months, and job training for the dryer operator is usually by trial and error. Therefore, dryer maintenance, supervision, and operation are far from optimal (OTA, 1989). The most frequent mistake is using excessively high temperatures in order to increase dryer capacity; for example, conventional cross-flow dryers normally use drying air temperatures from 80 to 110°C (see Table 2-8). Thus the grain processing quality tends to fluctuate (OTA, 1989).

On top of that, the performance of a grain dryer can be affected by the accuracy of the measurement of grain moisture and drying air temperature in the dryer (OTA, 1989). Commercially available electronic moisture meters used at grain drying facilities have an accuracy of ± 1 percent at the 13 to 16% moisture range and up to ± 3.0 percent at higher moistures (Hurburgh and Hanzen, 1984, see also Section 2-4-2). Air temperature measurement in a grain dryer is usually accomplished by a single thermocouple or thermistor, but the temperature distribution in the dryer is not even in many off-farm and on-farm dryers (OTA, 1989; Brooker et al., 1992). This results in over-heating of parts of grain lots in the dryer and deterioration of average grain quality, particularly in conventional cross-flow dryers (OTA, 1989; Zhang and Litchfield, 1991). Recently developed automatic dryer controllers for continuous flow dryers equipped with a computer (such as fuzzy logic or expert controller), can help improve dryer performance, minimize energy consumption, improve grain quality and reduce labour and errors by the dryer operator (Zhang and Litchfield, 1994; Bakker-Arkema et al., 1996). Notwithstanding the substantial costs, dryer control systems are economically justified on many grain dryers (Bakker-Arkema et al., 1996).

b) Initial moisture content

The initial moisture of grain when entering a dryer has a significant effect on dryer performance, particularly dryer capacity and energy consumption, and thus on grain quality (e.g., stress cracking and breakage susceptibility). When grain is harvested above its optimum harvest moisture, quality losses during drying increase (OTA, 1989; Weller et al., 1990). Certain years will be wet in the summer and autumn and result in grain with excessively high moisture content reaching the dryers. This leads to lower dryer capacity, higher drying cost, and decreased grain quality. In this condition, low temperature in-bin drying may not be able to dry wet grain before microbial infection occurs and thus farmers prefer to use high temperature drying methods that are less affected by weather conditions (OTA, 1989; Brooker et al., 1992).

This high temperature drying, however, may decrease maize quality. Particularly, grain harvested at moisture contents above 30% can readily be influenced exposure to by high temperature. Stress cracking and breakage susceptibility increase in such grains, and this lowers the processing quality (Thompson and Foster, 1963; Peplinski et al., 1975; Brown et al., 1979; Gunasekaran and Paulsen, 1985; Moes and Vyn, 1988; Weller et al., 1990). Peplinski et al. (1982) reported that maize harvested at 25% or less moisture and dried at 82°C or lower air temperatures would yield optimum dry milling results. In a recent study Weller et al. (1990) evaluated the effects of grain moisture content at harvest on stress cracking and breakage susceptibility in dried, hand-shelled maize grain. They found that stress cracks increased significantly as harvest moisture increased from 18 to 30% whether the drying air temperature was 49, 71, or 93°C.

c) Drying air temperature

Drying air temperature is one of the major process variables affecting dryer performance and grain quality, especially breakage susceptibility, stress cracking and milling quality of maize. Increasing drying air temperature increases breakage susceptibility and stress cracking and therefore lowers maize milling quality (Thompson and Foster, 1963; Brekke et al., 1973; Peplinski et al., 1982; Gunasekran et al., 1985; Kirleis and Stroshine, 1990; Meas et al., 1998, see also Section 2-3-2).

The effects of drying air temperature on maize quality, especially stress cracking and breakage susceptibility have been the subject of extensive studies (Thompson and Foster, 1963; White and Ross, 1972; Gunasekran et al., 1985; Litchfield and Okos, 1988; Sarwar et al., 1989; Kirleis and Stroshine, 1990; Peplinski et al., 1994). Thompson and Foster (1963) firstly noted that high-temperature (60-115°C) drying induced stress cracking in maize grain and those grains were two to three times more susceptible to breakage than the same maize grains dried with unheated air. Many studies have supported this work and most researchers found that increasing breakage susceptibility was associated with stress cracking mainly due to high-temperature, rapid drying and rapid cooling (White and Ross, 1972; Sarwar et al., 1989; Kirleis and Stroshine, 1990; Gunasekaran and Muthukumarappan, 1993).

Heat-induced grain damage such as stress cracking and breakage susceptibility subsequently influences maize milling quality (see also Section 2-3-2). Maize dried with high drying air temperatures decreases the yield of prime size grits and has more germ attached to the large flaking grits than that dried with unheated air (Brekke et al., 1973; Peplinski et al., 1989).

Severely stress-cracked maize grains steep more rapidly during the wet milling process, lose part of their starch in the steep water and this lowers starch recovery (Weller et al., 1988). Those grains also break easily when handled and broken grains greatly increase dry matter loss during alkaline processing (Jackson et al., 1988). High drying air temperatures also change the chemical properties of maize (e.g., protein denaturation), lower germination and viability (Wall et al., 1975; Navratil and Burris, 1984; Seyedin et al., 1984; Herter and Burris, 1989; Peplinski et al., 1994; Thuy, 1998), and lower nutritional value (Brooker et al., 1992). Finally, such grains lower the market value (OTA, 1989).

Therefore certain ranges of drying air temperatures have been recommended for a specific end use of maize. For example, a maximum temperature of 44°C for seed use, 55-60°C for starch production (wet milling) (Paulsen et al., 1996; Watson, 1987a), and 82°C for animal feed and dry milling (Peplinski et al., 1982) have been recommended (Muckle and Stirling, 1971; Salunkhe et al., 1985). However, these recommendations are for air temperatures, not the grain temperatures. For example, typical maximum grain temperatures recommended are 38-43°C for seed use (Hill, 1999).

d) Hybrid

Genotype also determines the drying rate (Gunasekaran and Paulsen, 1985; Stroshine et al., 1986), and stress cracking and breakage susceptibility of maize after drying (Paulsen, 1983; Paulsen et al., 1983b; Weller et al., 1990; Kirleis and Stroshine, 1990).

For example, Table 2-10 shows genotype differences for drying rate and breakage susceptibility of maize grain dried at various drying air temperatures. Both hybrids increased drying rate and breakage susceptibility as drying temperature increased from 20 to 65°C, but FRB27 x Va22 dried faster and had higher breakage susceptibility than FRB27 x Mo17, especially at higher drying temperatures (Gunasekaran and Paulsen, 1985).

Table 2-10. The effect of genotype difference on drying rate and breakage susceptibility of maize grain dried at various drying air temperatures (Gunasekaran and Paulsen, 1985).

Drying air temperature (°C)	**Genotype: FRB27 x Mo17**		**Genotype: FRB27 x Va22**	
	Drying rate[†] (kg/hr/kg x 10^{-3})	**Breakage[‡] susceptibility (%)**	**Drying rate (kg/hr/kg x 10^{-3})**	**Breakage susceptibility (%)**
20	3.38	2.54	5.02	2.14
35	10.41	4.36	12.20	11.10
50	18.91	12.19	29.92	20.41
65	37.02	14.19	60.79	28.25

[†]Grain was hand-harvested at about 27% moisture content and then hand shelled before drying in a laboratory dryer. Drying rate was calculated as the average moisture removal as grain was dried from 25 to 15% moisture content (kg / hour / kg of grain).
[‡]Breakage susceptibility was measured with a Stein breakage tester at room temperature (21°C) at a grain moisture content of 13.7 to 14% for both hybrids.

As discussed previously, however, hybrids which dry down rapidly in the field are more desirable because there is a reduced risk of quality deterioration from microbial infection or from frost damage in the field, and as less fuel is needed for the drying process drying costs are reduced (Stroshine et al., 1981; Bakker-Arkema et al, 1983; Stroshine et al., 1986).

Substantial moisture variation of maize grains within a hybrid due to different grain positions in the maize cob from the tip to the butt normally occur, and this also causes non-uniform drying (Bakker-Arkema et al., 1996). The moisture variation in the wettest and driest grains is higher in late maturity hybrids than in early maturity hybrids (i.e., fast dry down in the field). Within a hybrid the tip grains contain on average about 5% less moisture than the butt grains (Bakker-Arkema et al., 1996). Therefore, for a specific dryer operating for maize, the moisture variation within grains should be considered along with other dryer parameters such as drying time, drying temperature, and energy use and efficiency (Bakker-Arkema et al., 1996).

D. Stress cracking in maize grain

Among cereal grains, stress cracking in rice and maize grains is of considerable concern due to the potential grain quality deterioration during subsequent handling (Watson, 1987b; Brooker et al., 1992; Eckhoff and Paulsen, 1996). Stress cracking (i.e., fissuring) in maize grain is generally associated with rapid drying of maize with high drying air temperatures followed by rapid cooling (Thompson and Foster, 1963; Hill, 1999).

Maize lots with high stress-crack levels are more susceptible to breakage during subsequent handling and such grains lower the end use value of maize (Watson, 1987a; Eckhoff and Paulsen, 1996). Thompson and Foster (1963) first identified the type of stress cracking in artificially dried maize. The first indication of drying stress is a single crack usually extending from the tip toward the crown of the maize grain which is visible on the side of the grain opposite to the germ. As stress increases, multiple cracks develop and some grains end up with a checked or crazed appearance (Zhu and Cao, 1996, see also Figure 2-7).

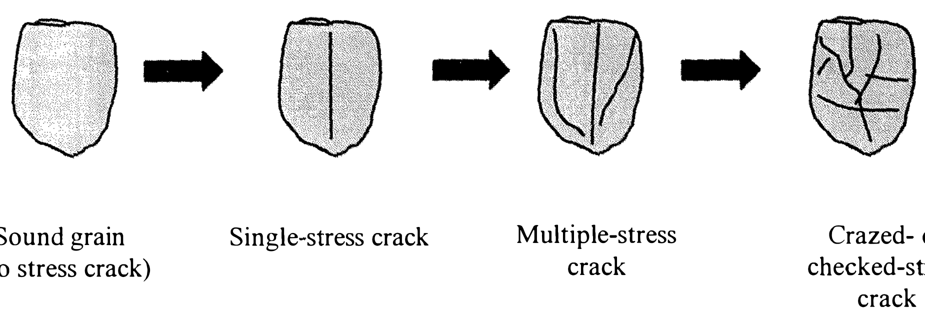


Figure 2-7. A schematic of stress cracks in maize grain (Thompson and Foster, 1963).

Note: Stress cracking develops in sequential order as indicated by the arrows, from single to multiple and checked (crazed) type.

Several researchers have studied and attempted to explain the development of stress cracking in cereal grains (Thompson and Foster, 1963; Kunze and Hall, 1965; Ekstrom et al., 1966; Kunze and Choudhury, 1972; Kunze, 1979; White et al., 1982; Sarwar and Kunze, 1989; Sarker et al., 1996; Lan and Kunze, 1996). However, most of the theories about stress cracking have been developed by Kunze at Texas A&M University in the USA.

Recently, Kunze (1996) reviewed studies on the development of fissures in a low moisture (dried) rice grain and suggested two distinctive mechanisms: 1) from moisture re-adsorption and 2) from rapid drying (to near storage moisture or below). However, in both cases, he explained that the development of stress cracks was due to an increase in the moisture gradient between the interior and outer layer of the grain.

Kunze's theory is based on the hygroscopic (hysteresis) (i.e., differences in moisture adsorption and desorption of grain at a given relative humidity (Christensen et al., 1992)) property of cereal grain:

1) From moisture re-adsorption (hygroscopic); when the low-moisture (dried) grain readsorbs moisture from any source to which it is exposed, the starch cells around the grain surface expand and produce compressive stresses. When the compressive stresses at the surface exceed the tensile strength of the grain at its centre, a fissure develops.
2) From rapid drying; as the moisture gradient declines after drying, the grain surface receives moisture from the interior and expands, while the grain interior loses moisture and contracts. As this combination of stresses (compressive at the surface and tensile at the centre) develops with time, the grain fails in tension by pulling itself apart at its centre (Kunze, 1996).

Balastreire et al. (1982) and Gunasekaran et al. (1985) also supported this idea, after optical and scanning electron microscopic observation. From their results, stress cracks originate at the inner core of the floury endosperm and propagate radially outward along the boundary of starch granules. However, they found that many cracks did not advance far enough to open up at the surface underneath the pericarp. Gunasekaran et al. (1985) found that an average stress crack was measured to be 58 ± 14 μm in width at its widest part.

Thompson and Foster (1963) suggested that stress cracking occurred during high temperature drying, especially rapid drying at grain from a moisture content of 19% down to 14%. However, Kunze (1979) and other researchers working with rice suggested that grain fissures in the grain do not develop during drying (Sharma et al.,

1979) and that it is the moisture gradient created during the drying period which provides the potential for later damage (Kunze and Choudhury, 1979; Sarker et al., 1996). In addition, White et al. (1982) in their experiments with popcorn, observed that very few grains had developed stress cracks at the time the grain was removed from the dryer. Instead stress cracks developed after the grains were stored for a period of time.

Since most grains are not fissured immediately after drying, a post drying treatment or procedure can prevent stress cracking. The most beneficial post-drying treatment is tempering the grain for a certain period of time before cooling (Thompson and Foster, 1963; Gustafson et al., 1983). Slow cooling after drying results in a dramatic reduction in the number of stress-cracked grains (Thompson and Foster, 1963; White and Ross, 1972). Short term tempering and multipass, multistage drying have been shown to be effective as well (Foster, 1973; Emam et al., 1979; Gustafson et al., 1983). In addition, reducing the drying air temperature and airflow rate also help minimize stress cracking (Thompson and Foster, 1963; Ross and White, 1972; Zhu et al., 1997).

2-6. Summary and conclusions

Recent increases in maize use for human consumption have emphasized the need for quality maintenance of maize grain. Figure 2-8 summarizes several maize production management factors that can influence grain quality attributes, particularly those relevant to the maize milling industry, grain hardness, breakage susceptibility and stress cracking.

Quality characteristics of maize required by the milling industry differ depending on the processing technology and the final products (Table 2-1). Maize hybrids containing soft endosperm are preferred by wet millers because a softer grain requires less steeping time and gives better starch/protein separation (Paulsen et al., 1996). On the other hand, the dry milling industry and alkaline processes are looking for hard endosperm maize that can produce high quality grits and masa (Eckhoff and Paulsen, 1996). In this respect, grain hardness is an important intrinsic quality property of maize because it affects grinding power requirements, yields of dry-milled products and is related to breakage during harvesting and postharvest handling. The harder the grain, the higher the yield of large flaking grits used to make corn flakes for breakfast cereals (Watson, 1987a; Peplinski et al., 1989; Good and Hill, 1992).

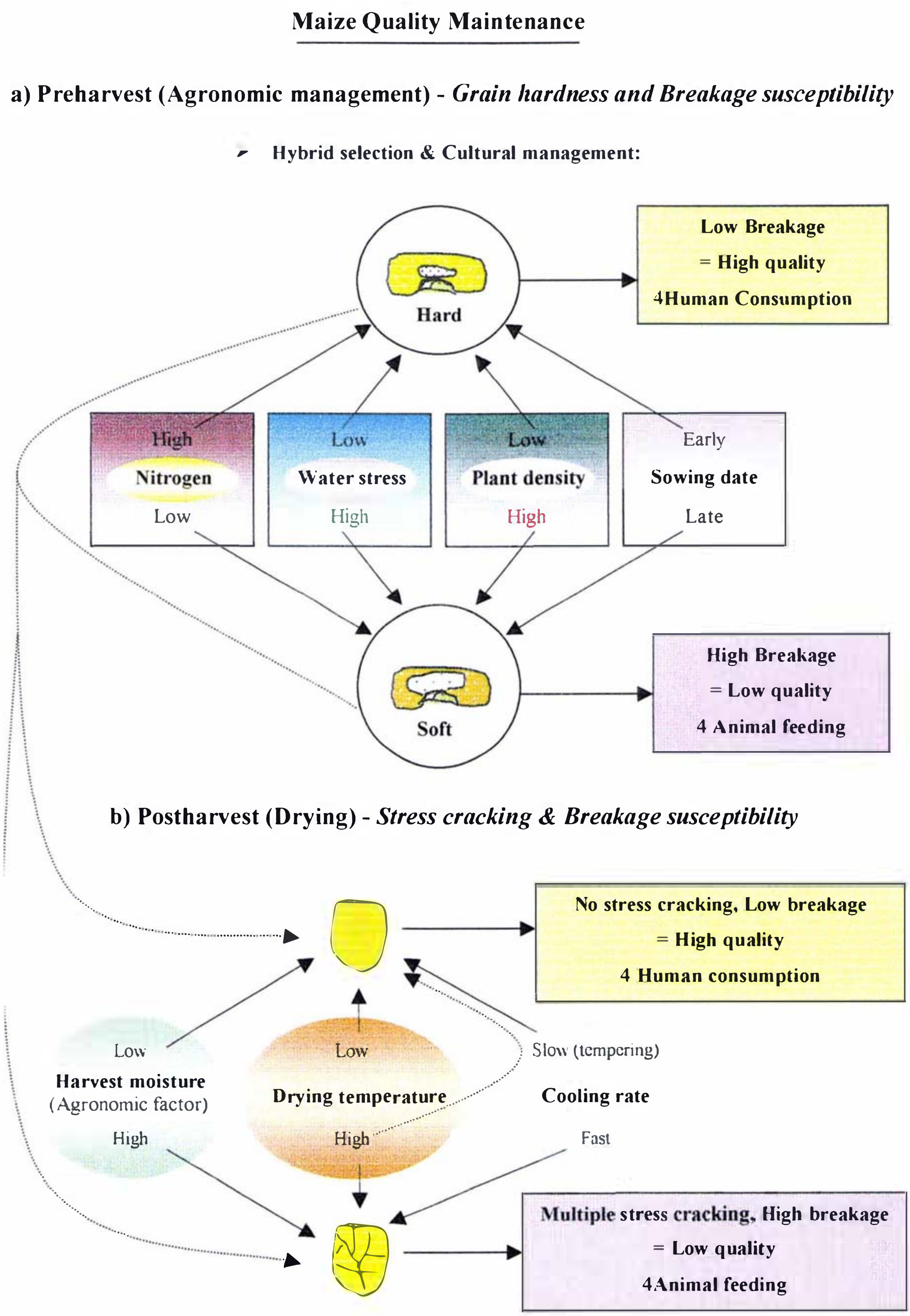


Figure 2-8. Maintenance of maize quality for human consumption.

Note: solid arrows indicates a direct effect; dotted arrows indicates an alternative (or optional) effect.

Grain hardness, a viscoelastic nature of maize, is also related to grain density, bulk density, and breakage susceptibility (Pomeranz et al., 1984). Generally as maize hardness increases, grain density increases, bulk density increases, and the grain shows a greater resistance to grinding. On the other hand, breakage susceptibility rather than grain hardness is more related to other grain characteristics such as size, shape and structure of the maize grain, which can be influenced by preharvest cultural management factors and postharvest drying (Paulsen et al., 1983b; Martin et al., 1987, see also Figure 2-8).

The quality of maize produced by farmers varies greatly because of differences in soils, climate, insects, disease, hybrids, and management practices with respect to harvesting, drying and storing (Bauer and Carter, 1986; Watson, 1987a; Amhadi et al., 1995). In practice, insufficient fertilizer nitrogen, late sowing, high plant densities, severe water stress and using a hybrid with inappropriate maturity will lower the dry milling quality of maize grain (Hardacre, 1994, see also Figure 2-8). For example, if maize harvesting is delayed due to climate or hybrid maturity, maize yield and quality may decrease due to microbial infection or frost damage. However if harvesting is too early, and thus grain moisture is too high (above 30%), maize grain will be soft and easily damaged during machine harvesting and high temperature drying (Figure 2-8). Such grains are more brittle and lower the maize grade and market value (Watson, 1987a).

The best hybrid that can be grown under a given season and area is of foremost importance to produce maize for a specific end use. For example, for dry milling, it has been recommended to select a hybrid with hard endosperm, rapid drying rate in the field and resistance to stress cracking during the drying process (Brenton-Rule et al., 1996; Eckhoff and Paulsen, 1996; Hardacre and Pyke, 1998a).

On top of that, there should be a correct way of drying, dryer selection and operating (e.g., drying air temperature, cooling method) for the specific end use of the maize (OTA, 1989; Brooker et al., 1992; Hardacre and Pyke, 1998a, see Figure 2-8 and Table 2-11). As seen in Table 2-11, if maize grain is used for poultry or livestock, the development of stress cracks during the drying process are of less concern. However, maize for dry milling, wet milling and alkaline processing should be prevented from developing stress cracks, because of the potential for deterioration in quality.

Table 2-11. Physical quality characteristics of maize grain and its end use.

Grain quality	**Physical characteristics**			**End use**
	Breakage	**Stress cracking**	**Grain hardness**	
High	Low	Non	Soft	Wet milling (starch)
			Hard	Dry milling (grits) / Alkaline processing (masa)
Low	High	Multiple or Checking	Soft Hard	Animal feeding

Overall, this review has shown that several agronomic and postharvest drying factors affect grain physical properties and development of stress cracking. However, new maize hybrids are developed and commercialized on a regular basis to meet specific industry needs. Further research is highly warranted to characterize their drying performance including breakage and development of stress cracking during postharvest drying. In the next Chapters, the main research works on this will be further discussed including; the effects of preharvest and postharvest factors on stress cracking in maize and the effects of grain temperature on grain breakage susceptibility.

Chapter 3 Effects of pre-harvest and postharvest factors on grain quality attributes, drying characteristics, and stress cracking in three maize hybrids

3-1. Introduction

Several studies have shown that maize grain hardness and breakage susceptibility are inherited characteristics (Johnson and Russell, 1982; Paulsen et al., 1983b), indicating that these physical characteristics could be improved by proper hybrid selection and crop management.

One of the most important cultural practice related to grain hardness and breakage susceptibility is the use of nitrogen fertilizer (Hamilton et al., 1951; Bauer and Carter, 1986). Recent studies have shown that higher soil nitrogen levels increased grain hardness (i.e., increased the ratio of horny to floury (hard to soft) endosperm) and apparently reduced breakage susceptibility, and could improve maize dry milling quality (Sabata and Mason, 1992; Ahmadi et al., 1995; Patwary, 1995; Oikeh et al., 1998).

Although hybrid selection and crop management can produce improved grain physical quality attributes, improperly controlled drying may reduce grain quality (Brooker et al., 1992). Particularly, problems can be compounded when grain harvested at high moisture contents (above 30%) is subjected to exposure to high drying-air temperatures. Weller et al. (1990) found that stress cracks increased significantly as harvest moisture increased from 18 to 30% whether the drying air temperature was 49, 71, or 93°C.

Stress cracking in grains due to drying stress associated with high temperature rapid drying and large amount of moisture removal could be reduced if grains are cooled slowly after drying. This beneficial post-drying treatment, so called, 'dryeration' (i.e., tempering the grain for a certain period of time before cooling) has long been noted (Thompson and Foster, 1963; Gustafson et al., 1983) and applied in practice with multipass, multistage drying systems. However, on the grounds of expense there is resistance to the use of tempering bins and thus dryeration (Bakker-Arkema et al., 1996; Hansen et al., 1996).

Nitrogen availability and harvest moisture are important agronomic factors that may affect grain quality and drying performance. However, there has been little information about harvest moisture and nitrogen effects on drying performance and maize quality as indicated by stress cracking. The aim of this study was to evaluate the drying performance and stress cracking of three commercially grown maize hybrids as affected by pre-harvest and post-drying treatments. The specific objectives were to:

1. determine the effect of hybrid, nitrogen, and harvest moisture on grain yield and physical attributes including bulk density, grain dimension, and hardness (hard to soft endosperm ratio),

2. determine the effect of hybrid, nitrogen, harvest moisture and drying temperature on drying time and drying rate and,

3. determine the effect of hybrid, nitrogen, harvest moisture, and drying and cooling rate on stress cracking in maize grain.

3-2. Material and methods

3-2-1. Plant material

In this study, three commercially grown maize hybrids (Furio, Pioneer 3902, and Pioneer 3753) were used. These are early maturing hybrids suitable for cool or short season areas such as the Manawatu in New Zealand (Eagles and Hardacre, 1985; Brenton-Rule et al., 1996). These hybrids differ in shape, size, and hardness. P3753 grains are relatively small in size and slightly flat compared to the other two hybrids. P3902 grains are more rounded. For grain hardness Furio is rated as soft, P3753 intermediate and P3902 hard (Li et al., 1996).

3-2-2. Field trial design and cropping management

A. Experimental design of field trial

The field trial design was a split-split plot (Figure 3.1). The trial was conducted at Massey University (40° 23'S) on a mottled, fine sandy loam soil. There were three blocks and within each block main plots were two levels of applied nitrogen; within each main plot (nitrogen), three maize hybrids were randomized. Each hybrid sub-plot was again divided into two levels of grain moisture at harvest. Each sub-plot was 12m (16 rows with 0.75m interval between rows) in width and 3.75m (25 stations within a row with 0.15m interval between stations) in length. Two rows (1.5m) between sub-plots were not sampled (buffer rows), while four extra rows (3m) were planted as guard rows on the outside of each block. In each row, five plants (0.75m) between the sub-plots and between blocks were not used for sampling (Figure 3-1).

B. Planting and cropping management

Planting date was 20th of November, 1995. The trial site was ploughed one month before sowing and was harrowed two days before sowing. A pea crop had been grown at this site in the previous year. A furrow was created for each row by a hand-held grubber before planting. Seeds were sown by hand in the furrowed row at approximately 5cm depth. To ensure adequate plant establishment and allow for population adjustment, one or two seeds were planted at each 15-cm station and then rows were thinned by hand at about the 4-5-leaf stage to 25 plants for a plant density of 89,000 plants per hectare, which is commonly used for commercial maize production in New Zealand (Douglas et al., 1982; Underwood, 1985; Hardacre et al., 1992).

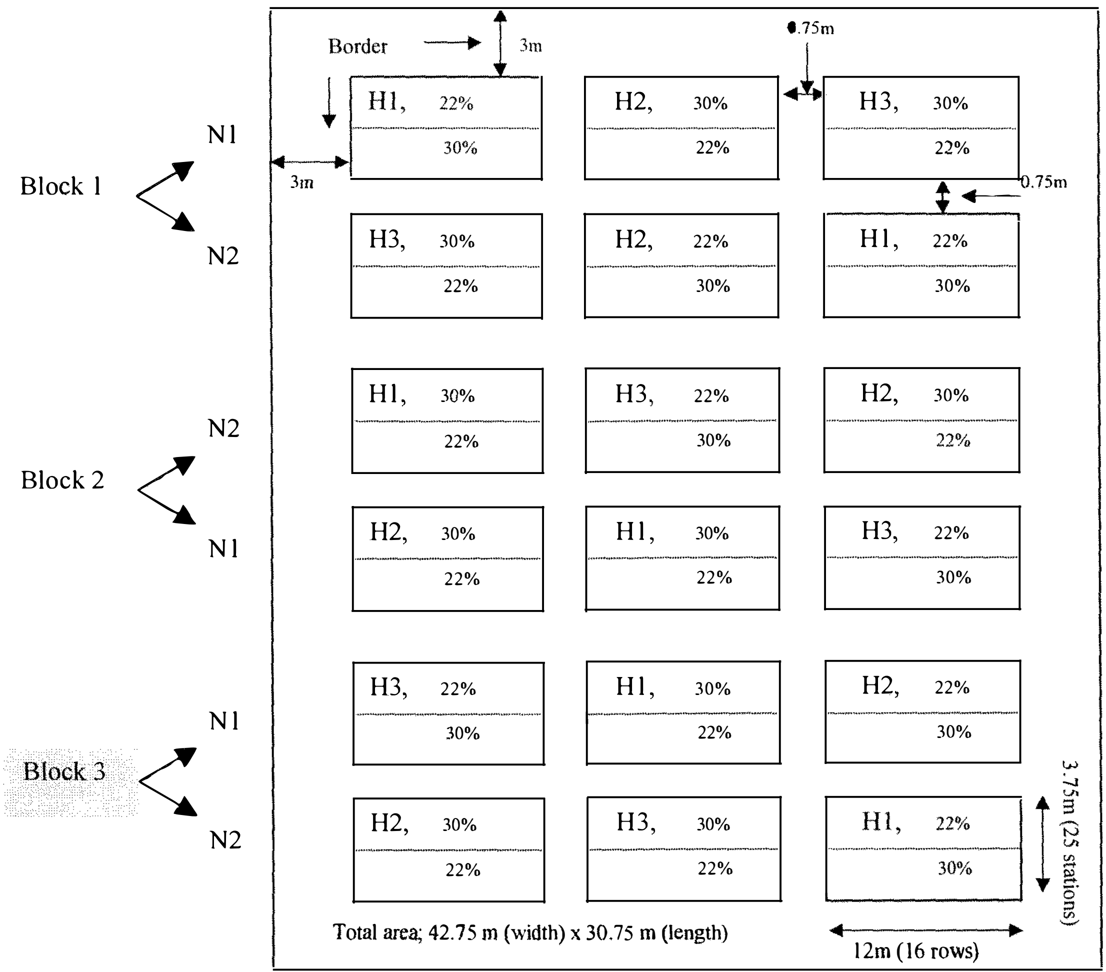


Figure 3-1. The layout of the field trial in the 1995/96 season.

Note: N1; 0 kg N/ha, N2; 230 kg N/ha, H1; Furio, H2; P3753, H3; P3902, 22% and 30%; targeted moisture content of maize grain at harvest

Mr. A. K. Hardacre, Crop & Food Research Ltd, Palmerston North provided the three seed lots. Seeds were treated with an insecticide (Promet 300EW) at a rate of 40 ml/kg (12 g/kg of furathiocarb) of seed prior to sowing. The pre-emergence herbicides, Alachlor and Atrazine were applied one day after sowing (21st of November) at a rate of 7 l/ha for Alachlor^{480EC} (3.36 kg/ha alachlor) and 3 l/ha for Gesaprim^{500FW} (1.5 kg/ha atrazine). Any subsequent weeds were then removed by hand. After signs of infestation by cutworm (*Agrotisipsilon aneituma* Walker) (Scott, 1984), Hallmark^{5EC} was applied at a rate of 450 ml/ha (22.5g/ha esfenvalerate; for protecting plant samples, the application rate was nearly twice the standard recommendation) to control the cutworm at the 2-3 leaf stage (about one month after sowing (11th of December)).

C. Nitrogen treatment

The side-dressing nitrogen (N) treatments were 0 and 230 kg N/ha, with the N being applied as urea (46% N) at four times to avoid the loss of nitrogen by leaching and volatilization. The first application of urea (46 kg N/ha) was made at 25 days after sowing (DAS), the second and third applications (both 46 kg N/ha) were added at 35 DAS and 60 DAS, and the last application (92 kg N/ha) at 83 DAS.

D. Harvesting and sampling

In each plot two of the centre rows were selected for monitoring grain moisture. Maize grain moisture in the field was monitored each week from physiological maturity (approximately 60% grain moisture content) to final harvest to determine harvest time. For each assessment two cobs were randomly collected from each plot and grains were selected from two adjacent rows of the cob from the upper to the lower end. Grain moisture content was determined using the oven method described in the next section (see 3-2-4. A).

To determine the number of grains per cob (NOG), hundred grain weight (HGW), grain yield, bulk density, grain dimension and hardness (hard to soft endosperm ratio), hand-picked primary cobs (i.e., the cob located in the lowest position in the maize plant) from ten maize plants in each replicate were dehusked and dried at ambient temperature (approximately 20^{o}C, 65 RH) to an average of 11% grain moisture. All cobs were then hand-shelled after drying and grains were stored at room temperature before testing. NOG, HGW, grain yield and bulk density were determined for grains harvested at both

22% and 30% grain moisture, but grain dimension and hardness were determined only for maize samples harvested at 30% grain moisture.

3-2-3. Postharvest maize drying and cooling procedure

The drying experiment was conducted in a laboratory where the temperature was approximately 20°C and relative humidity approximately 65-70%. Figure 3-2 provides a flow diagram for the drying and cooling procedures for the 1996 drying experiment.

For the drying experiment, approximately 40 cobs (12 kg) were hand-harvested from each plot in the afternoon before a drying test. Due to differences in maturity and field dry down rate of the maize hybrids, the rate of drying among the plots were different. The cobs were hand shelled at room temperature and very small grains from the shelled maize were removed through a 6.75mm hole sieve. Grains were then sealed in a plastic bag and stored overnight in a 5°C room (see also Plate 3-1 and 3-2). The harvest moisture was determined by the two stage moisture test (ISTA, 1996, see also 3-2-4. A) using 20g sub-samples drawn from each sample, and was recorded (Appendix 1).

Before drying, about 300g of grains were weighed, the weight recorded, and then the grains were spread evenly over the bottom of the drying tray in a single layer (Plate 3-3). Drying trays used in this experiment were made of metal and had a bottom surface area of 640.9cm^2 (14.5cm x 44.2cm). The bottom of the drying tray was made of 0.3mm-wire mesh and the height of the drying tray was 7cm. Each drying tray was divided into half for two cooling rates after drying. The drying trays containing grains were then re-weighed before drying and put inside the drying ovens, which were controlled at 50, 60, 70 or 80°C ± 2°C. The drying trays were positioned in a random order inside the oven. An extra drying tray was re-weighed at 30 minute intervals for 4 hours and then at 60 minute intervals after 4 hours drying at each drying temperature until the desired grain moisture (see below) was reached.

When the grain moisture reached about 17%, one of the drying trays was removed from the oven for a 45°C cooling treatment. The others were removed when the grain moisture reached about 15%. Soon after removal from the dry oven, each drying tray containing the dried grains was weighed quickly and the grain surface temperature measured by using an infrared thermometer (Plate 3-4). Grains were then poured into a 250ml polystyrene cup and placed into the cooling conditions (45, 25, or 5 ± 1°C). During cooling, one polystyrene cup was covered and sealed with a lid to simulate slow cooling and the other was left open for fast cooling at each cooling temperature (Plate 3-5). The covered polystyrene cup was put into a polystyrene box and the box was sealed tightly to reduce further direct contact with ambient air.

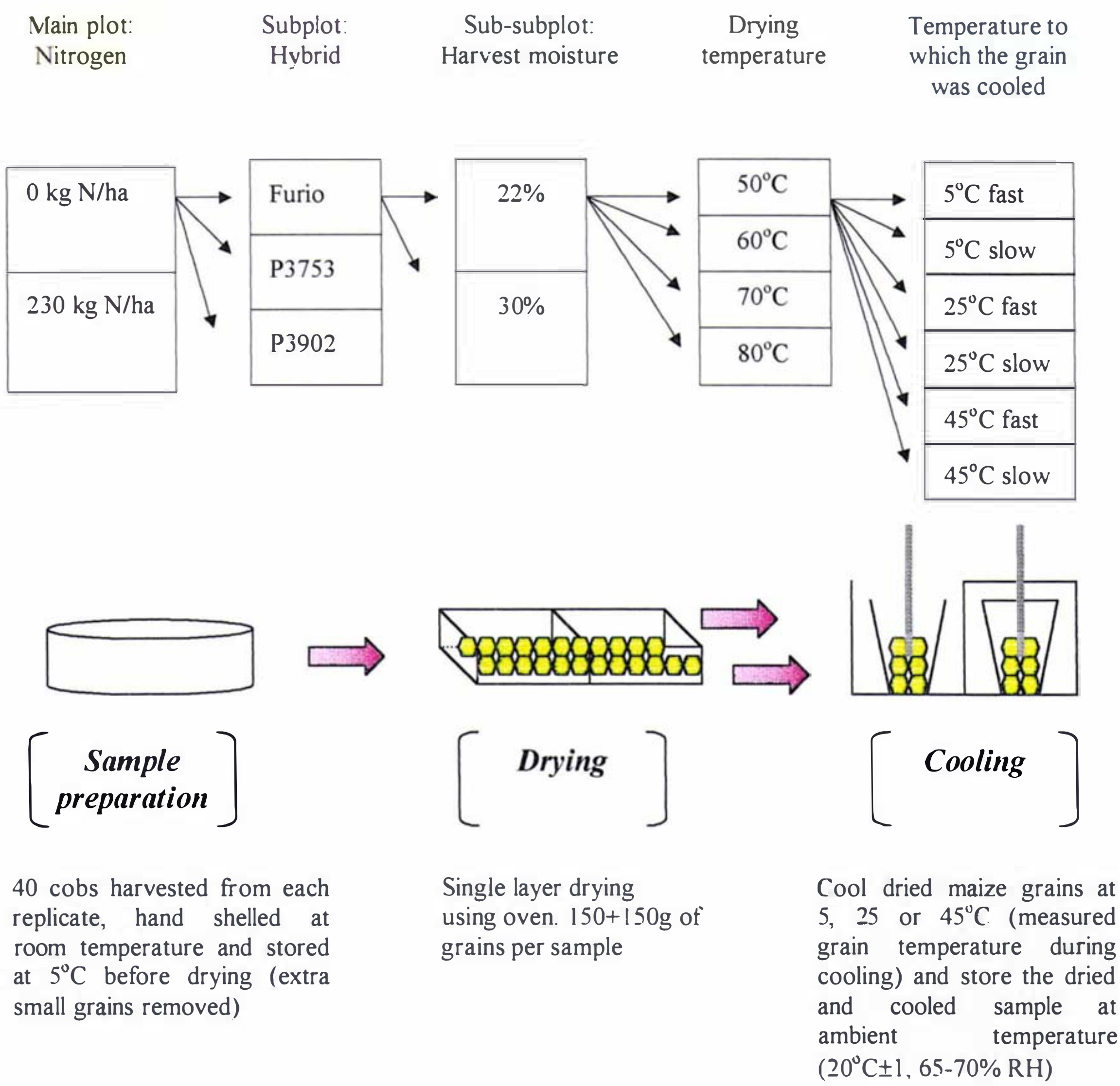


Figure 3-2. The drying and cooling procedure for the 1996 drying experiment.

Plate 3-1. Hand shelling of maize grain after harvest from the field. Very small grains which passed through 6.75mm-hole sieve were removed.

Plate 3-2. Storage of hand-shelled grains before drying. Grains were placed into a plastic bin, tightly sealed with plastic bags, and stored at 5°C for 24 to 48 hours before drying at various drying air temperatures.

Plate 3-3. Arrangement of maize grains in a single layer in the drying trays before drying.

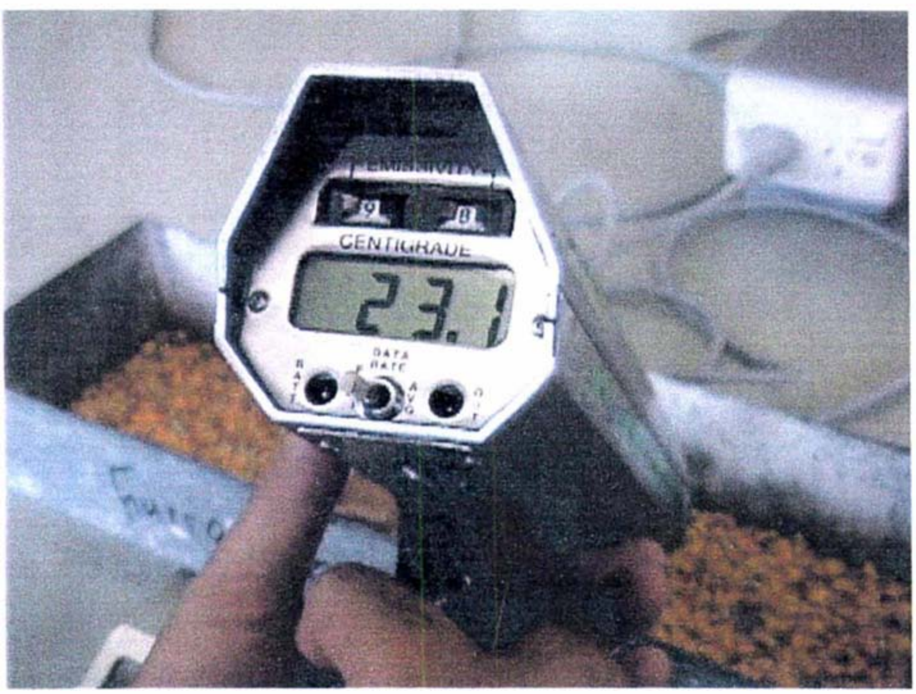
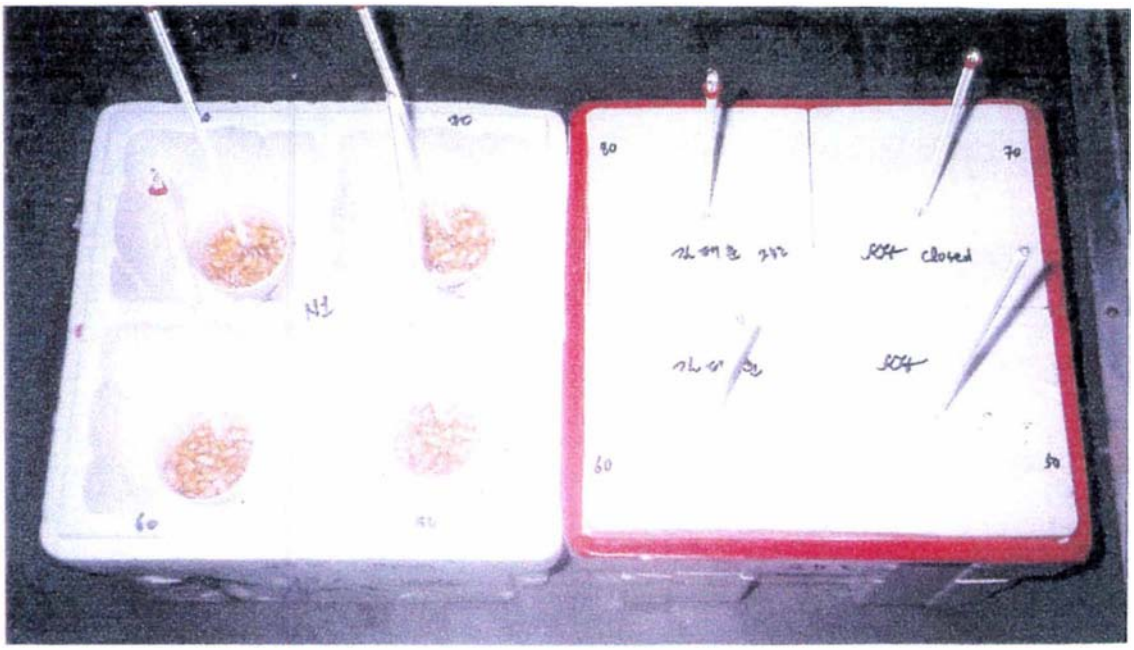


Plate 3-4. An example of measuring an instant grain surface temperature by using an infrared thermometer (The infrared thermometer in this photo indicates a surface grain temperature of 23.1°C, the air temperature was 25°C).



A B

Plate 3-5. Grain cooling systems for A: fast cooling (left); grains were uncovered during cooling, and B: slow cooling (right); grains covered tightly by a tightly sealed polystyrene cover. Grain temperature was measured via an inserted thermometer in each grain lot.

For the 45°C cooling, grains were tempered at 45 ± 1°C for 4 hours in an incubator and then grains were cooled at 25°C for 20 hours (Figure 3-7), while for the 25 and 5°C cooling, grains were left for 24 hours at each cooling temperature. During cooling, grain temperature in the cup was periodically recorded by monitoring via an inserted thermometer (see Plate 3-4). After being cooled to the desired temperature, the samples were placed in ambient conditions (approximately 20°C and 65% relative humidity) for 4 weeks for moisture equilibration before stress cracking assessment.

3-2-4. Laboratory measurements

A. Grain moisture content

The moisture content of maize grains was determined according to International Seed Testing Association Rules (ISTA, 1996). Twenty grams of grain was sub-sampled from each replicate, and the moisture test was duplicated for each replicate using 10g of the sample. The two-stage moisture content test was used. As a first stage, the weighed grain sample was pre-dried in a warm place overnight before re-weighing. As a second stage, the pre-dried grain sample was then ground in a hammer mill and dried for 4 hours at 130°C in an oven as prescribed by ISTA (1996) and then cooled in a desiccator before re-weighing. The percentage moisture content on a wet weight basis was calculated from the weight loss obtained in the first and second stages of the procedure using the following formula (equation (3.1)):

$$\text{Grain moisture content (\%)} = S_1 + S_2 - \left(\frac{S_1 \times S_2}{100} \right) \quad \text{--------} \ (3.1)$$

where,

S_1 = the moisture content in the first stage,

S_2 = the moisture content in the second stage.

The moisture content in the first and second stage (S_1 and S_2) was calculated to one decimal place by means of the following formula (equation (3.2)) as recommended by ISTA (1996):

$$\text{Moisture content of } S_1 \text{ or } S_2\ (\%) = \left(\frac{(m_2 - m_3)}{(m_2 - m_1)} \right) \bullet 100 \qquad \text{--------- (3.2)}$$

(g/g; wet weight basis)

where,

m_1 = the weight in grams of the container and it's cover,

m_2 = the weight in grams of the container, it's cover and it's contents before drying,

m_3 = the weight in grams of the container, cover and contents after drying.

B. Grain yield and yield characteristics

As described previously, ten maize plants were randomly selected from each replicate to determine grain yield and yield characteristics at the two targeted-harvest grain moisture contents of 30% and 22%. Grain yield was calculated using the following formula (Patwary, 1995, equation (3.3)):

$$\textit{Grain yield (tonne / hectare) } Y = (P \bullet NC \bullet NOG \bullet ((HGW / 100))\ (g)) \bullet 10^{-6} \qquad \text{--------- (3.3)}$$

where,

P = Plant population per hectare (89,000 plants per hectare),

NC = Number of cobs per plant,

NOG = Number of grains per cob,

HGW = 100-grain weight (g).

The number of cobs per plant was counted in the field at each harvest; there was no significant difference in the number of cobs per plant among hybrids, nitrogen levels and harvest moistures (about 1.0 cob per plant). Using only 10 of the primary maize cobs, the number of grains per cob was determined by multiplying the number of grains in a vertical line in the cob and the number of grains in a horizontal line in the middle of the cob. Hundred-grain weight was determined by measuring the weight of 100 grains for each replicate and it was then adjusted to 14% grain moisture content; thus the grain yield was expressed at 14% grain moisture content, which is normally recommended for a safe storage level of grain.

C. Bulk density

Bulk density of grain harvested at both 22 and 30% grain moisture was determined by weighing the sample grain at approximately 11% moisture content. An aluminum bin (a volume of 259.05ml) was used for determining grain bulk density. Grains were placed into this bin until it was full (level with the top), the volume of grain was weighed. Grain bulk density was then calculated as follows (equation (3.4)):

$$\text{Bulk Density (BD) (kg/hl)} = \left(\frac{\text{Grain weight (g)}}{\text{Volume of the grain with void space (259.05 ml)}} \right) \bullet 10^2 \quad \text{---------} (3.4)$$

The bulk density then was re-calibrated using the following formula (equation (3.5)) suggested by Hardacre et al. (1997):

$$\text{Bulk Density (BD) at 14\%} = \text{BD of grain} + (0.3 \times (MC_a - 14)) \quad \text{----------} (3.5)$$

where, MC_a is the moisture content (MC) of the maize sample at the time of testing. For example, if a grain sample at 23% MC has a BD reading of 70.0 kg/hl, its corrected BD at 14% MC will be 72.7 kg/hl, i.e., assuming for every 1% decrease in moisture there will be a 0.3 kg/hl increase in bulk density (Hardacre et al., 1997).

D. Grain dimension and roundness

Dimensions of an individual maize grain were measured by hand with a digital caliper using 25 grains randomly selected from the ambient dried samples that were harvested at 30% grain moisture.

Assuming the grain was a triaxial ellipsoid with intercepts a (length), b (width), and c (thickness) (Figure 3-3) and the diameter of the circumscribed sphere was the longest intercept of the ellipsoid, the degree of sphericity (Roundness) was calculated as (Mohsenin, 1970; Martin et al., 1987, equation (3.6)):

$$\text{Sphericity (Roundness)} = \left(\frac{\text{Volume of solid}}{\text{Volume of circumscribed sphere}}\right)^{1/3}$$

$$= \frac{(abc)^{1/3}}{a} \qquad \text{---------------} \ (3.6)$$

where,

a (length) = longest axis,

b (width) = longest axis normal to a,

c (thickness) = longest axis normal to a and b (see also Figure 3-3).

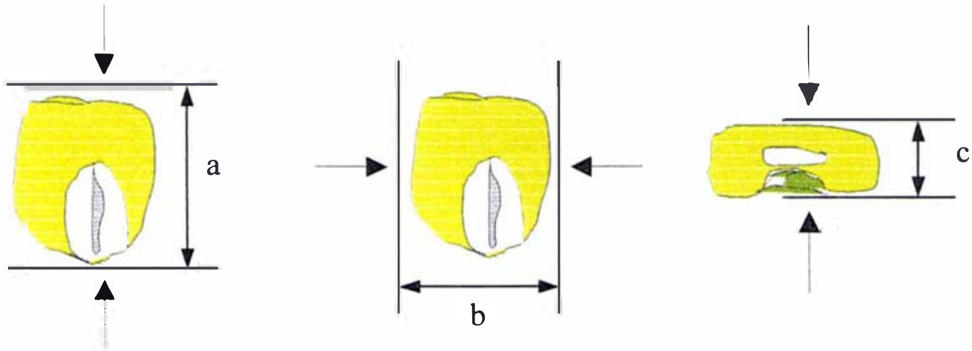


Figure 3-3. Measurement of maize grain dimension (a: Length, b: Width, c: Thickness).

E. Hard to soft endosperm ratio (H/S ratio)

Maize hardness can be defined by the ratio of hard and soft endosperm (Watson, 1987a). In this experiment, the hard to soft endosperm ratio (H/S ratio) of maize grain was determined by using 25 grains harvested at 30% grain moisture.

After drying, each grain was sectioned just above the top of the embryo region (about 2/3 of the distance from the tip cap to the crown) using a knife (Figure 3-4) and the H/S ratio was then determined using the following formula (Kirleis et al., 1984, equation (3.7)):

$$\text{Hard to soft endosperm ratio (H/S ratio)} = \frac{(T_a - S_a)}{S_a} = \frac{H_a}{S_a} \quad \text{----- (3.7)}$$

where,

T_a = Total area (mm^2); ($L_a \bullet L_b$)

S_a = Soft endosperm area (mm^2); ($L_c \bullet L_d$)

H_a = Hard endosperm area (mm^2); (T_a- S_a) = ($L_a \bullet L_b$) – ($L_c \bullet L_d$)

L_a, L_b, L_c, and L_d are defined as total width, total length, soft endosperm width, and soft endosperm length, respectively and these parameters were used for calculating the approximate total cut-surface area (T_a), soft endosperm area (S_a), and hard endosperm area (H_a), respectively (Figure 3-4).

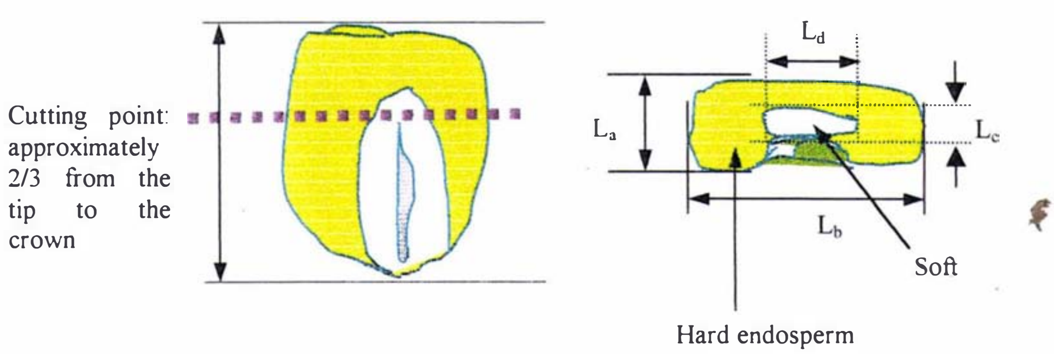


Figure 3-4. Sectioning of maize grain for measuring the ratio of hard to soft endosperm, where L_a, L_b, L_c, and L_d are defined as total-sectioned width and length, width and length of soft endosperm area, respectively.

F. Stress cracks

Stress cracks in maize grains were determined using a 50g sub-sample of each replicate after finishing the drying and cooling. Each grain was candled for stress crack evaluation by placing it on a small square of glass laid on the opening in a box containing a 22-watt round fluorescent lamp. The grains were examined after holding the grain both embryo side down and up to the light source. Grains were then classified into four stress-crack categories i.e. none, single, multiple, and checked (crazed) (Figure 3-5). Several soft grains had non-detectable stress cracking due to their low translucency (chalky endosperm) and these were regarded as sound grains (no stress cracking). The percentage of grains in each category was then calculated using the following formula (equation (3.8)):

$$\text{Stress crack (\%)} = \left(\frac{\text{Numbers of stress cracked grains in each category}}{\text{Numbers of whole grains}} \right) \bullet 100 \qquad \text{------------ (3.8)}$$

Samples usually contained from about 130 to 170 whole grains and took 15 or 20 minutes to inspect. After determining the percentage of stress cracks in each sample, a stress crack index (SCI) was calculated using the following equation (Kirleis and Stroshine, 1990, equation (3.9)):

$$\text{SCI} = \text{\% single cracked grains} + 3\,(\text{\% multiple cracked grains}) + 5\,(\text{\% checked grains}) \qquad \text{----------- (3.9)}$$

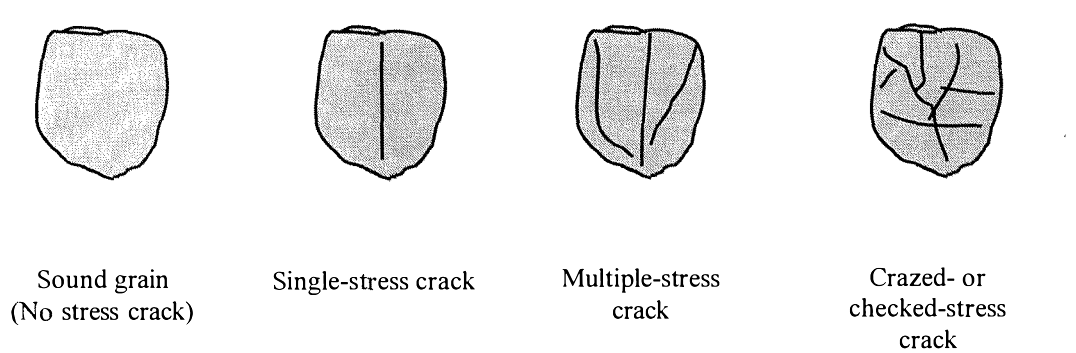


Figure 3-5. A sketch of various types of stress cracks in maize grain.

3-2-5. Calculation of drying rate and cooling rate

A. Drying time and drying rate

The relative drying time (t_{15}) was calculated from the drying curve and defined as the time taken to dry down to 15% grain moisture content, which means the duration from the initial moisture content to dry-down to 15% (wet basis) (Figure 3-6). In this experiment, an average drying rate was determined from the average moisture removal from 20% to 15% moisture content (wet basis) in order to present the relative drying rate of maize harvested at two different grain moisture levels of 22% and 30%.

The relative drying rate was determined using the following formula (Gunasekaran and Paulsen, 1985, equation, (3.10)):

$$\text{Relative Drying rate (kg/hr/kg)} = \left(\frac{(MC_{20} - MC_{15})}{(t_{15} - t_{20})} \right) \quad \text{-------- (3.10)}$$

where, MC_{15} and MC_{20} are actual grain moisture contents at 15% and 20% on the curve and t_{15} and t_{20} mean the drying time (minute) taken to get grain to 15 and 20% moisture content, respectively (see Figure 3-6). The relative drying rate was then expressed as the average moisture removal in kg of water per hour per kg of grain (kg/hr/kg).

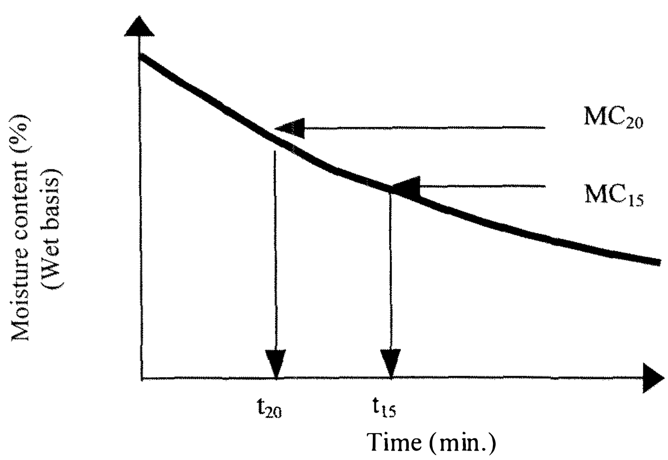


Figure 3-6. An example of calculating drying time and drying rate from the drying curve, where MC_{15}, and MC_{20} indicate the grain moisture content at 15% and 20%, and t_{15} and t_{20} indicate the time taken to reach these moisture contents.

B. Cooling rate

Figure 3-7 shows cooling curves at average grain temperature at approximately 3-4cm depth in the middle of approximately 120-140g of maize grain during cooling under static conditions for each cooling treatment (see also Plate 3-4).

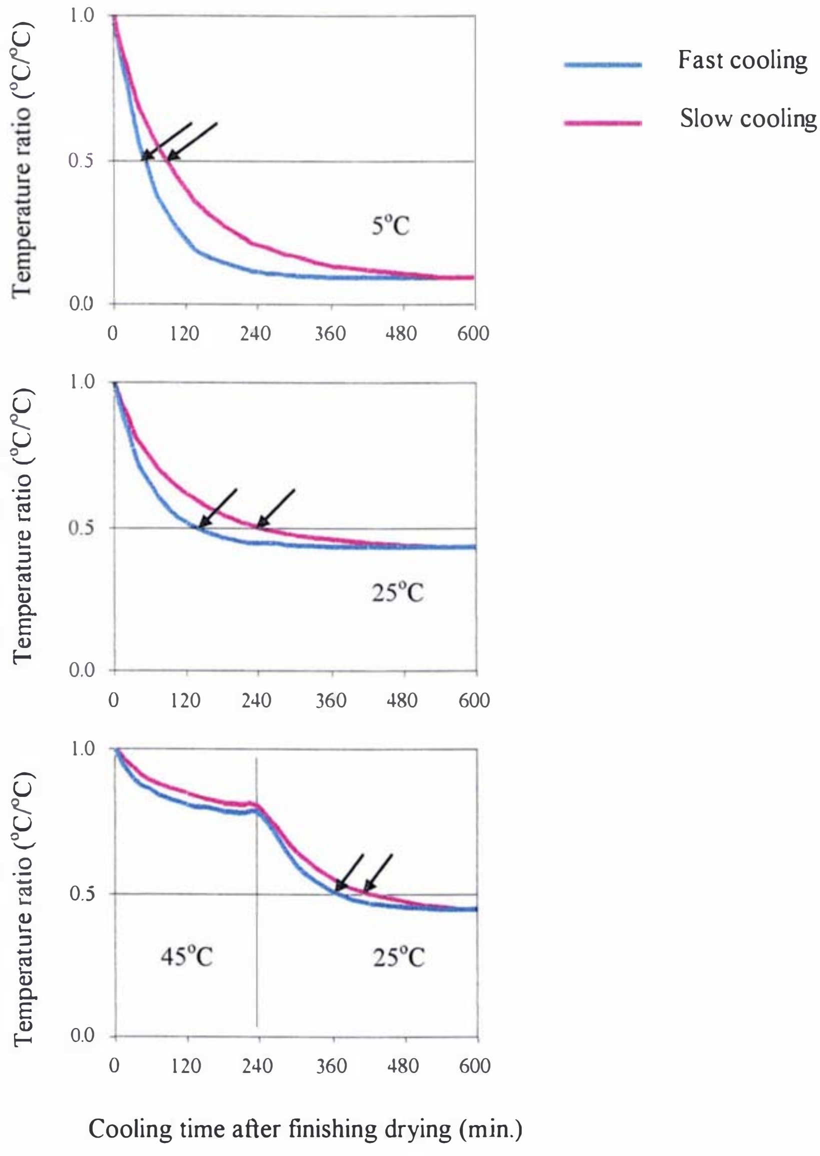


Figure 3-7. Average curves during cooling at various cooling temperatures (5, 25, and 45°C) and for the two different cooling systems (fast (=open) and slow (=closed)) at each cooling temperature, Plate 3-4).

$$\text{Temperature ratio } (TR_i)\ (^\circ C/^\circ C) = \frac{(GT_0 - GT_i)\ (^\circ C)}{GT_0\ (^\circ C)}$$

where, GT_0 = The average grain temperature at the starting of cooling, GT_i = The average grain temperature at i^{th} time, TR_i = Temperature ratio at i^{th} time (minute) from the starting of cooling.

Note: The arrows indicate the cooling time taken to reach half of the starting grain temperature at each cooling curve.

In this Figure, the sample mass and moisture content are regarded as the same and were ignored, and the temperature ratio (TR_i) at the i^{th} time (minute) from the start of cooling was determined using the following formula (equation (3.11)):

$$\text{Temperature ratio } (TR_i) = \frac{(GT_0 - GT_i)}{GT_0} \quad \text{---------------- } (3.11)$$

where,

GT_0 = The average grain temperature at the starting of cooling,

GT_i = The average grain temperature at i^{th} time.

Consequently, TR_0 (i.e., the temperature ratio at 0 minute after cooling) equals one in this relationship (Figure 3-7). The relative cooling rate of grain during cooling was then defined as the average temperature ratio (°C/°C) reduction per time (minute) and it was determined by the following formula (equation (3.12)):

$$\text{Cooling rate (CR) } (^{o}C/^{o}C/\text{min.}) = \frac{(TR_i - TR_j)}{t_j - t_i} \quad \text{----- } (3.12)$$

where,

TR_i and TR_j = The temperature ratio at i^{th} and j^{th} time (minute) after the start of cooling,

t_i and t_j = The time (minute) after the start of cooling.

In this study, cooling rates (°C/°C/min.) were determined at 30 minute intervals based on the observation of grain temperature measurement. Particularly, relative cooling rate between 0 and 30 minute after the start of cooling was applied to characterize the conditions of cooling or tempering in this experiment.

3-2-6. Data analysis

The grain yield and quality data including the number of grains per cob, hundred grain weight, grain yield, bulk density, grain dimension and hardness ratio were analyzed using analysis of variance (ANOVA) and general linear models (GLM) procedures in SAS (SAS, 1985) appropriate for a split-split-plot experimental design. With the occurrence of a significant ANOVA or GLM for main effects, means were tabulated using the least significant difference (LSD) option.

Significant interactions between independent variables were further investigated by plotting the data means on bar- or line-graphs and calculating LSD values appropriate for testing at a significance level of $P < 0.05$.

Drying time, drying rate, stress cracking and stress crack index (SCI) data were also analyzed using the same procedure and based on the observation an empirical model was fitted to predict the average SCI for maize hybrid, nitrogen, and drying temperature as a function of cooling rate according to the following regression equation (3.13):

$$\text{Stress Crack Index (SCI)} = \frac{A}{1 + B \bullet e^{-(C \bullet CR)}} \qquad \text{-------- (3.13)}$$

where,

A = asymptote,

B = constant for initial value of SCI,

C = rate increase in SCI to the asymptote within the range of drying air temperature of 50, 60, 70, and 80°C, and

CR = cooling rate (°C/°C/min.)$\bullet 10^{-2}$.

3-3. Results

3-3-1. The effect of nitrogen, hybrid and harvest moisture on grain yield and quality

A. Number of grains per cob, hundred-grain weight, grain yield and bulk density

Table 3-1 shows the effect of nitrogen, hybrid and harvest moisture on number of grains per maize cob, hundred-grain weight, grain yield and bulk density. The number of grains per cob, hundred-grain weight, grain yield and bulk density were significantly affected by both maize hybrid and applied nitrogen (Table 3-1).

Table 3-1. The effect of nitrogen, hybrid and harvest moisture on number of grains per maize cob, hundred grain weight, grain yield and bulk density.

		NOG†	**HGW (g)**	**Yield (t/ha)**	**Bulk Density (kg/hl)**
Hybrid (HYB)	Furio	511.0	30.9	14.3	72.2
	P3753	569.8	31.0	15.7	74.7
	P3902	504.7	32.2	14.8	76.2
Significance		***	**	*	***
LSD (5%, df_{error}=8)		23.2	0.7	1.0	0.4
Nitrogen (N)	0 kg N/ha	519.2	30.4	14.0	73.8
	230 kg N/ha	537.8	32.4	15.8	74.9
Significance		NS	*	*	*
LSD (5%, df_{error}=2)		-	1.8	1.6	0.5
Harvest moisture (HMC)	22%	522.9	31.6	14.9	74.5
	30%	534.1	31.1	14.9	74.2
Significance		NS	NS	NS	NS
		Interactions			
HYB x N		NS	**	NS	NS
HYB x HMC		*	NS	NS	NS
N x HMC		NS	NS	NS	NS
HYB x N x HMC		NS	NS	NS	NS

†Note: NOG=Number of grains per cob; HGW=Hundred grain weight. Yield and bulk density were adjusted to grain moisture content of 14% (wet basis). NS, *, **, or ***; Non significant or significant *F-test* at <0.05, 0.01, 0.001, respectively.

The hybrid P3753 had a significantly higher grain yield than the other two hybrids, but there was no significant difference in grain yield between P3902 and Furio. Bulk density was greatest in P3902, intermediate in P3753 and lowest in Furio (Table 3-1). Nitrogen application also significantly increased grain yield and bulk density, but as expected harvest moisture did not affect grain yield or bulk density (Table 3-1).

The only significant interactions among the variables were hybrid and nitrogen for hundred-grain weight, and hybrid and harvest moisture for number of grains per cob (Table 3-1 and Figure 3-8). The hybrid P3753 had a significantly greater number of grains at both 22% and 30% harvest moisture than the other two hybrids. Especially, plant samples in the field for P3753 lodged more than the other two hybrids. The cobs were also infected by mould and bird's attack at 22% harvest moisture. Grains shattered easily during de-husking in such damaged cobs (top part of the cob). Therefore it was difficult to calculate accurate number of grains per cob at 22% harvest, particularly that for P3753. However, grain number for P3902 and Furio did not differ significantly at either harvest (Figure 3-8, A).

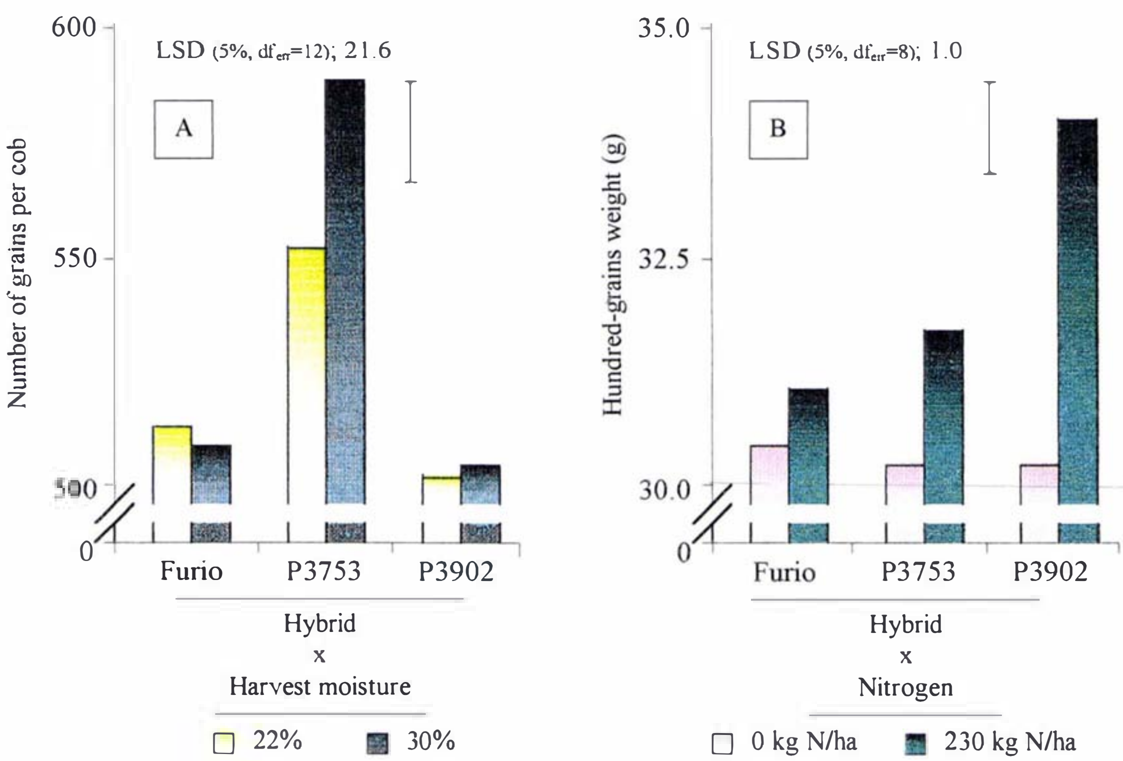


Figure 3-8. The interaction between hybrid (HYB) and harvest moisture (HMC) for the number of grains per cob (NOG) (A) and between hybrid (HYB) and nitrogen (N) for the hundred-grain weight (HGW) (B).

The three hybrids had a similar hundred grain weight (HGW) (about 30.4g) at 0 kg N/ha (Table 3-1 and Figure 3-8, B). As N level was increased from 0 to 230 kg N/ha, HGW of P3902 and that of P3753 increased significantly, about 13% for P3902 and 5% for P3753, respectively, but not for Furio. The HGW of P3902 was significantly greater at 230 kg N/ha than that of the other two hybrids, while those of Furio and P3753 did not differ significantly within the same level of N (Figure 3-8, B).

B. Grain dimension and hardness (hard to soft endosperm ratio (H/S ratio))

Grain dimension and roundness differed significantly among maize hybrids but not with applied nitrogen (Table 3-2). The three maize hybrids had similar grain width, but P3753 was the longest and the thinnest and P3902 was the shortest and the thickest. P3753 was the flattest and P3902 was the roundest grain among the three hybrids (Table 3-2). On the other hand, grain hardness (hard to soft endosperm ratio (H/S ratio)) was significantly affected by the interaction between hybrid and nitrogen (Table 3-2).

Table 3-2. The effect of hybrid and nitrogen on grain dimension, roundness, and hardness (hard to soft endosperm ratio).

		Length (a)[†] (mm)	Width (b) (mm)	Thickness (c) (mm)	Roundness	Hardness (H/S ratio)
Hybrid (HYB)	Furio	12.13	8.39	4.59	0.640	2.0
	P3902	11.63	8.31	4.92	0.671	2.7
	P3753	12.57	8.26	4.32	0.609	2.9
Significance		***	NS	***	***	**
LSD (5%, df_{err}=8)		0.27	-	0.18	0.016	0.5
Nitrogen (N)	0 kg N/ha	11.95	8.22	4.63	0.645	2.1
	230 kg N/ha	12.27	8.41	4.59	0.635	2.9
Significance		NS	NS	NS	NS	NS
				Interaction		
HYB x N		NS	NS	NS	NS	*

[†]Note: Grain length (a), width (b), thickness (c), and roundness, and grain hardness (H/S ratio) were determined as described in section 3-2-4. E and F (see also Figure 3-3 and 3-4), respectively. NS, *, **, or *** ; Non significant or significant *F-test* at <0.05, 0.01, 0.001, respectively.

P3753 had the highest H/S ratio at 0 kg N/ha among the three maize hybrids, but it did not significantly differ with those of Furio and P3902 (Figure 3-9). As nitrogen was increased from 0 to 230 kg N/ha, H/S ratio in the three hybrids increased by an average of 0.3, 0.6, and 1.5, in Furio, P3753, and P3902, respectively, but only the increase in H/S ratio of P3902 was statistically significant (Figure 3-9).

The increase in the H/S ratio of Furio was the smallest and Furio had a significantly lower H/S ratio than P3753 and P3902 at 230 kg N/ha. There was no significant difference in H/S ratio between P3902 and P3753 at 230 kg N/ha (Figure 3-9).

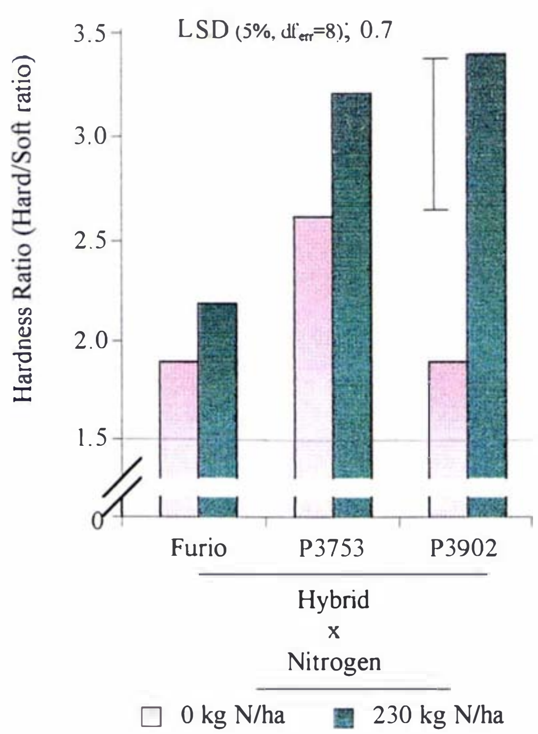


Figure 3-9. The interaction between hybrid and nitrogen for maize grain hardness (Hard/Soft ratio).

3-3-2. Drying and cooling performance

A. Drying time and drying rate

Table 3-3 shows the effect of hybrid, nitrogen, harvest moisture, and drying temperature on drying time and drying rate of maize grain. The drying time (duration) was defined as the duration from an initial moisture content to 15% moisture content. The drying rate was calculated by the average moisture removal in kg of water per hour per kg of grain from 20% to 15% moisture content from each drying curve (See also Section 3-2-5, A. Figure 3-6).

From preliminary data analysis, treatment effects including hybrid, nitrogen, harvest moisture, and drying temperature on drying time and drying rate were multiplicative. The data were log-transformed (natural log) and re-analyzed. The figures in parentheses in Table 3-3 indicated the means from log-transformed data, significance levels and least significant differences (LSD) for log-transformed data.

Although the main effects of hybrid, nitrogen, harvest moisture and drying temperature for the drying time and drying rate were all significant, the drying time and the drying rate of grains were significantly affected by several two-way and three-way interactions among variables (Table 3-3).

The major interactions for drying time were among hybrid, harvest moisture and drying temperature (Figure 3-10 and Figure 3-11). At 50 and 60°C drying, the drying time differed significantly with hybrid for both the 22 and 30% harvest moisture (Figure 3-10 (c)). At 70 and 80°C drying, however, there was no significant difference in drying time between P3753 and P3902 at 22% harvest moisture, and Furio (soft) and P3753 had similar drying time at 30% harvest moisture (Figure 3-10 (c)). Drying time was also differed significantly with nitrogen at 50 and 60°C drying at 30% harvest moisture, but drying time between the two levels of nitrogen was similar at 70 and 80°C drying at 30% harvest moisture and at every drying temperature at 22% harvest moisture (Figure 3-11 (b)).

Table 3-3. The effect of hybrid, nitrogen, harvest moisture, and drying temperature on drying time and drying rate of maize grain.

		Drying Time ‡ (minute)		Drying Rate ((kg/hour/kg) •10^{-3})	
Hybrid (HYB)	Furio	136	(4.78)†	45.9	(3.73)
	P3753	152	(4.90)	46.0	(3.72)
	P3902	167	(4.99)	42.3	(3.63)
Significance		***	(***)	**	(**)
LSD (5%, df_{error}=8)		8	(0.04)	2.3	(0.04)
Nitrogen (N)	0 kg N/ha	148	(4.87)	46.2	(3.73)
	230 kg N/ha	155	(4.91)	43.3	(3.66)
Significance		*	(NS)	NS	(NS)
LSD (5%, df_{error}=2)		6	(-)	-	-
Harvest moisture (HMC)	22%	109	(4.60)	45.4	(3.71)
	30%	194	(5.18)	44.1	(3.68)
Significance		***	(***)	NS	(NS)
LSD (5%, df_{error}=12)		6	(0.04)	-	-
Drying temperature (DT)	50°C	230	(5.40)	23.6	(3.16)
	60°C	180	(5.14)	31.1	(3.43)
	70°C	121	(4.74)	46.9	(3.85)
	80°C	75	(4.28)	77.3	(4.34)
Significance		***	(***)	***	(***)
LSD (5%, df_{error}=72)		4	(0.02)	1.9	(0.03)
		Interactions			
HYB x N		NS	(NS)	NS	(NS)
HYB x HMC		NS	(NS)	NS	(NS)
HYB x DT		***	(**)	NS	(*)
N x HMC		NS	(NS)	NS	(NS)
N x DT		*	(NS)	*	(NS)
HMC x DT		***	(***)	NS	(*)
HYB x HMC x DT		**	(***)	NS	(*)
N x HMC x DT		*	(*)	NS	NS

‡Note: Drying time and drying rate were determined as described in section 3-2-5 A (see also Figure 3-6).

†Due to the abnormal distribution of residuals, the log-transformed data for drying time and drying rate were re-analyzed. NS, *, **, or *** ; Non significant or significant *F-test* at <0.05, 0.01, 0.001, respectively.

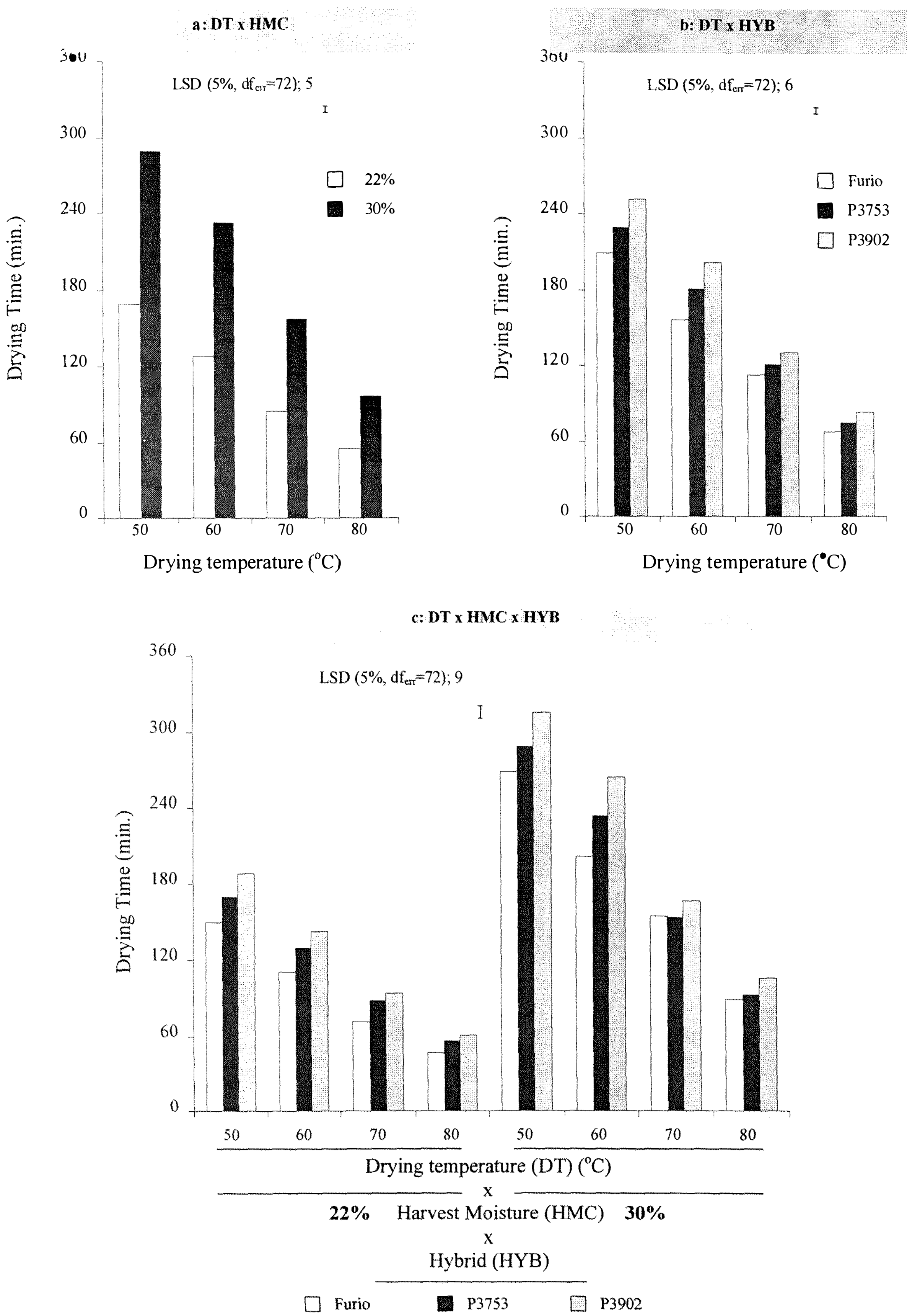


Figure 3-10. The interactions of harvest moisture and drying temperature (a), hybrid and drying temperature (b), and drying temperature, harvest moisture and hybrid (c) for drying time of maize grain.

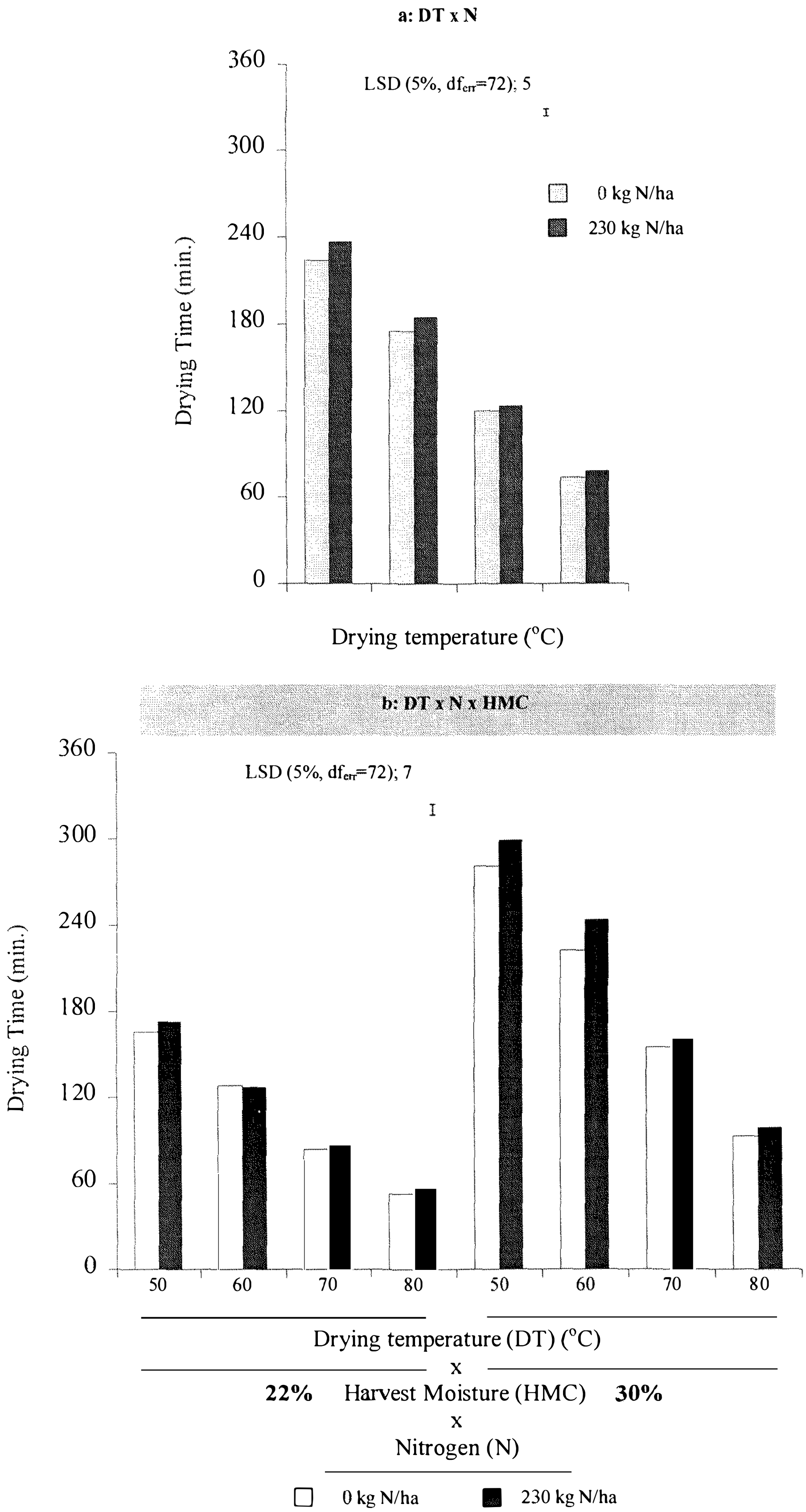


Figure 3-11. The interactions of nitrogen and drying temperature (a) and drying temperature, nitrogen and harvest moisture (b) for drying time of maize grain.

However, at each drying temperature, the proportional differences among the values presented in the five graphs in Figure 3-10 and Figure 3-11 were very similar. For example; as the drying temperature increased from 50°C to 80°C, the difference in drying time between 30% and 22% harvest moisture reduced significantly from about 120 minutes at 50°C to about 40 minutes at 80°C. However, the proportional difference in drying time between grain harvested at 22% and 30% moisture was similar regardless of drying temperature. For example, grain dried from 30% moisture took about 40% longer than grain dried from 22% moisture at 50°C, at 80°C the difference was again about 40% (Figure 3-10 (a)).

Therefore, the interactions among the variables for grain drying time and drying rate were of minor practical importance, and furthermore the F-values for the main effects, were much greater than those for the interactions (e.g., log drying time; F_{DT} (6335.29)>>>$F_{HYB \times DT}$ (10.02)).

The main effects of drying temperature on drying time and drying rate were highly significant. As the drying temperature increased from 50°C to 80°C, the average drying time reduced significantly (linearly) from 230 minutes to 75 minutes. On average the drying time for grain harvested at 30% harvest moisture was about 40% greater than for grain harvested at 22% (Table 3-3). The average drying time decreased significantly with hybrid in the order: P3902 > P3753 >Furio (Table 3-3). The soft grain hybrid Furio took about 20% less time to dry than the hybrid with the hardest grain P3902 at all drying temperatures.

Grain drying rate was not affected by nitrogen or harvest moisture (Table 3-3). As the drying temperature was increased from 50 to 80°C, the grain drying rate increased significantly and exponentially from 23.6 to 77.3 (kg/hr/kg)$\bullet 10^{-3}$, this corresponded to a percentage moisture loss rates between 2.4 and 7.7 percent per hour. Among the hybrids, P3902 had a significantly slower drying rate than the other two hybrids. There was no significant difference in drying rate between Furio and P3753 (Table 3-3). Arguments presented for the interaction terms for drying time can be applied to drying rate and it is not considered necessary to discuss these interactions.

B. Grain temperature and relative cooling rate of maize grain

The grain surface temperature recorded at the end of drying was obviously different among applied drying temperatures (Table 3-4). The difference between the grain surface temperature and the drying temperature at 50°C was small (only 2°C), but the difference between grain and drying temperature was increased as drying temperature increased (Table 3-4).

Table 3-4. Average grain-surface temperature at the terminal stage of drying at various drying air temperatures.

	Drying Temperature (°C)			
	80	**70**	**60**	**50**
Grain Temperature† (± 1°C)	71.5	59.0	53.0	48.0

†Note: grain surface temperatures were measured using an infrared thermometer just after the finish of drying at each drying temperature.

Table 3-5 presents the relative cooling rates for maize grain tempered at 45°C and cooled at 25°C and 5°C. The relative cooling rate (CR) of maize grain decreased from 0.81 to 0.23 (°C/°C/min.)•10^{-2} in the slow cooling system (i.e., grains were cooled in the tightly sealed polystyrene cup, Plate 3-4) and 1.11 to 0.34 (°C/°C/min.)•10^{-2} in the fast cooling system (i.e., grains were cooled in the polystyrene cup unsealed state, see also Plate 3-4) as the cooling temperature increased from 5°C to 45°C (Table 3-5).

Average cooling rate in the fast cooling system was about 30% higher than that of the slow cooling system within a cooling temperature. The difference in cooling rate of maize grain between the slow and fast cooling systems at 45°C was smaller than that at the 25 and 5°C cooling temperatures (Table 3-5). The highest cooling rate was recorded in the 5°C fast cooling system (1.11 (°C/°C/min.)•10^{-2}) and the lowest cooling rate was in the 45°C slow cooling system (0.23 (°C/°C/min.)•10^{-2})) (Table 3-5). These cooling rates (CR) created by the different cooling temperatures and cooling systems were later used for analyzing the data for stress cracking in maize grain that had been dried and cooled under various conditions (see the next section 3-3-3).

Table 3-5. Relative cooling rate (CR) in the slow and fast cooling systems at various cooling temperatures.

Cooling Temperature (°C)	Cooling Rate (CR) ((°C/°C/min.) •10^{-2}) Cooling System	
	Slow (open)	Fast (closed)
45[†]	0.23	0.34
25	0.55	0.75
5	0.81	1.11

[†]Note: Maize grain was tempered for four hours at 45°C prior to 25°C cooling for 20 hours. At 25 and 5°C, grains were cooled for 24 hours at each cooling temperature (See also section 3-2-5. B and Figure 3-7 and Plate 3-4).

3-3-3. Stress cracking

Table 3-6 presents the effects of hybrid, nitrogen, harvest moisture, drying temperature, and cooling rate on the percentage of various types of stress cracking and the stress crack index (SCI) in maize grains. The SCI, which represented the severity of stress cracking in grains, was calculated as equation (3.9), and instead of each category of stress cracking, SCI was compared for the effects of variables on the extent of stress cracking in grains.

The main effects of all the variables including hybrid, nitrogen, harvest moisture, drying temperature, and cooling rate on stress cracking were significant. Among the agronomic factors, the effect of hybrid on stress cracking was most significant. The two hybrids, Furio and P3753 had a similar SCI and they had a significantly higher SCI than P3902. The SCI also increased significantly as nitrogen and harvest moisture increased. However, the percentage of checked stress cracking in grains did not differ significantly as nitrogen and harvest moisture increased (Table 3-6).

The effects of postharvest drying factors including drying temperature and cooling rate on stress cracking were also significant. As drying temperature increased from 50 to 80°C, the percentage of multiple and checked stress cracking and SCI increased significantly, but there was no significant difference in SCI and the percentage of multiple and checked stress cracking for grains dried at 60 and 70°C. As cooling rate increased from 0.23 to 1.11 (°C/°C/min.)•10^{-2}, SCI in grains increased significantly. Particularly, the difference in SCI was the greatest at the range of cooling rates between 0.34 and 0.55 (°C/°C/min.)•10^{-2} (Table 3-6).

Table 3-6. The effects of hybrid, nitrogen, harvest moisture, drying temperature, and cooling rate on the percentage of various types of stress cracking and the stress crack index (SCI) in maize grains.

		Types of stress cracking[†] (%)				Stress Crack Index (SCI)[‡]
		NSC	SSC	MSC	CSC	
Hybrid (HYB)	Furio	26.7	10.0	51.3	12.1	224.2
	P3753	25.7	12.2	53.1	9.0	216.4
	P3902	40.0	18.3	39.8	1.9	147.3
Significance		***	***	***	***	***
LSD(5%, df_{err}=8)		4.3	2.5	3.1	3.3	11.9
Nitrogen (N)	0 kg N/ha	33.6	13.7	46.3	6.4	184.8
	230 kg N/ha	28.0	13.3	49.9	8.8	207.1
Significance		*	**	NS	NS	**
LSD(5%, df_{err}=2)		3.8	0.1	-	-	9.7
Harvest Moisture (HMC)	22%	35.2	12.5	44.8	7.5	184.4
	30%	26.4	14.5	51.3	7.8	207.4
Significance		***	*	***	NS	**
LSD(5%, df_{err}=12)		3.7	1.9	2.9	-	14.2
Drying Temperature (DT)	50°C	37.0	16.2	42.2	4.7	166.1
	60°C	30.6	13.2	48.0	8.2	198.2
	70°C	30.5	12.5	48.8	8.2	199.8
	80°C	25.0	12.2	53.3	9.5	219.7
Significance		***	***	***	***	***
LSD(5%, df_{err}=72)		1.8	1.1	1.6	1.1	6.6
Cooling rate (CR)[#]	0.23	77.7	16.7	5.5	0.1	33.6
(°C/°C/min.) $\bullet 10^{-2}$	0.34	63.8	19.7	15.5	1.0	71.3
	0.55	16.3	18.2	60.4	5.2	225.2
	0.75	10.2	10.2	68.7	10.8	270.7
	0.81	8.3	8.8	70.3	12.6	282.7
	1.11	8.4	7.5	68.0	16.1	292.1
Significance		***	***	***	***	***
LSD(5%, df_{err}=480)		1.8	1.5	1.8	0.9	5.2
		Interactions				
HYB x DT		NS	***	***	***	**
HMC x DT		***	**	NS	NS	*
HYB x CR		***	***	***	***	***
N x CR		NS	**	NS	***	***
HMC x CR		***	***	***	NS	***
DT x CR		***	***	***	***	***
HYB x N x CR		NS	*	***	*	NS
HYB x HMC x CR		**	NS	***	NS	***
HMC x DT x CR		***	***	**	NS	*
HYB x DT x CR		NS	***	***	***	***

[†] Note: NSC = non-stress-cracking, SSC = single stress cracking, MSC = multiple stress cracking, and CSC = checked stress cracking.

[‡] Stress Crack Index (SCI) = %Single + 3•(%Multiple) + 5•(%Checked)

[#] The cooling rates created by the different cooling temperatures and cooling systems were calculated using the formula described in section 3-2-5. B (see also Table 3-6).

NS, *, **, or *** ; Non significant or significant *F-test* at <0.05, 0.01, 0.001, respectively.

Although stress cracking in grains was significantly affected by the main effects, there were significant, although small two-way and three-way interactions among the variables for stress cracking and SCI (Table 3-6).

The two hybrids, Furio and P3753 had a similar SCI in most cases. Although the differences in stress cracking and SCI between Furio and P3753 were statistically significant, they were small and for all practical purpose negligible. For example; these hybrids had a SCI value of more than 300 regardless of drying temperature and harvest moisture at cooling rates between 0.75 and 1.11((^{o}C/^{o}C/min.)•10^{-2}) (Figure 3-14 (a and c)).

The hybrid P3902 had significantly lower SCI than Furio and P3753 at the same harvest moisture, drying temperature, and cooling rate (Figure 3-12 (a) and (d), Figure 3-13 (a) and (c)). At cooling rates of 0.23 and 0.34 ((^{o}C/^{o}C/min.)•10^{-2}), the absolute differences between the hybrids were small and were proportionally similar to those at faster cooling rates. The interaction terms were therefore, of little use in interpreting these data.

Stress cracking and SCI values were significantly reduced as harvest moisture reduced from 30% to 22%, particularly at lower cooling rates between 0.23 and 0.34 (^{o}C/^{o}C/min.)•10^{-2}). However, at higher cooling rates between 0.55 and 1.11 (^{o}C/^{o}C/min.)•10^{-2}), the difference in stress cracking and SCI values between the two harvest moisture levels of 22 and 30% was small at the same level of hybrid, drying temperature and cooling rate, and negligible in terms of practical importance (Figure 3-12 (e) and Figure 3-14 (a and b)).

The interactions among the variables for stress cracking and SCI were, however, relatively minor practical importance, when compared to the *F*-values of the main effects (e.g., SCI cooling rate; F_{CR} (3695.19)>>>F_{HYBxCR} (54.97)). The interactions might occur due to the different cooling speed between the outer layer (upper part) and inner layer of the grains in the polystyrene cup as grains were cooled at fast cooling system.

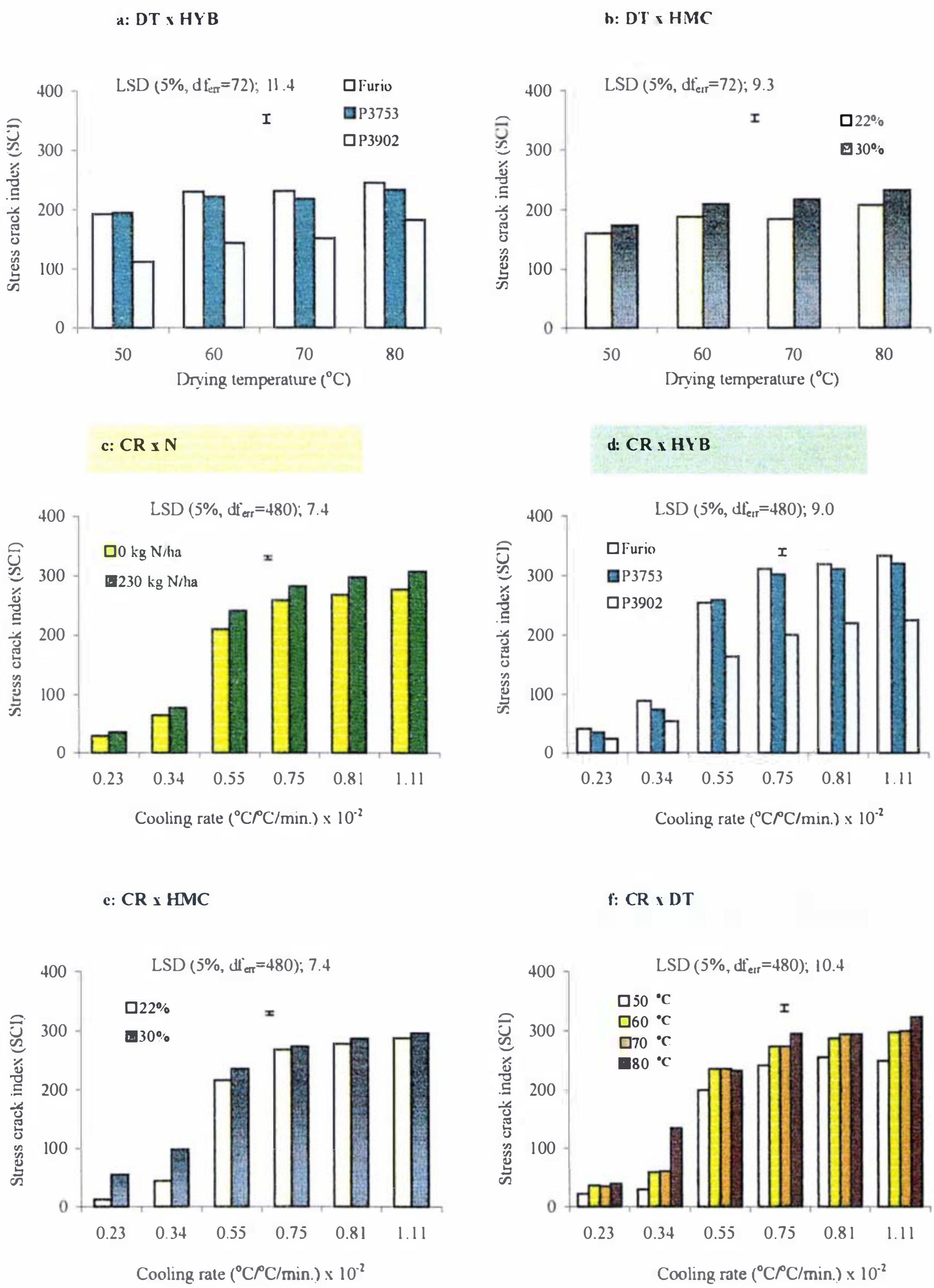


Figure 3-12. Two-way interactions among hybrids, nitrogen, harvest moisture, drying temperature, and cooling rate for stress crack index (SCI).

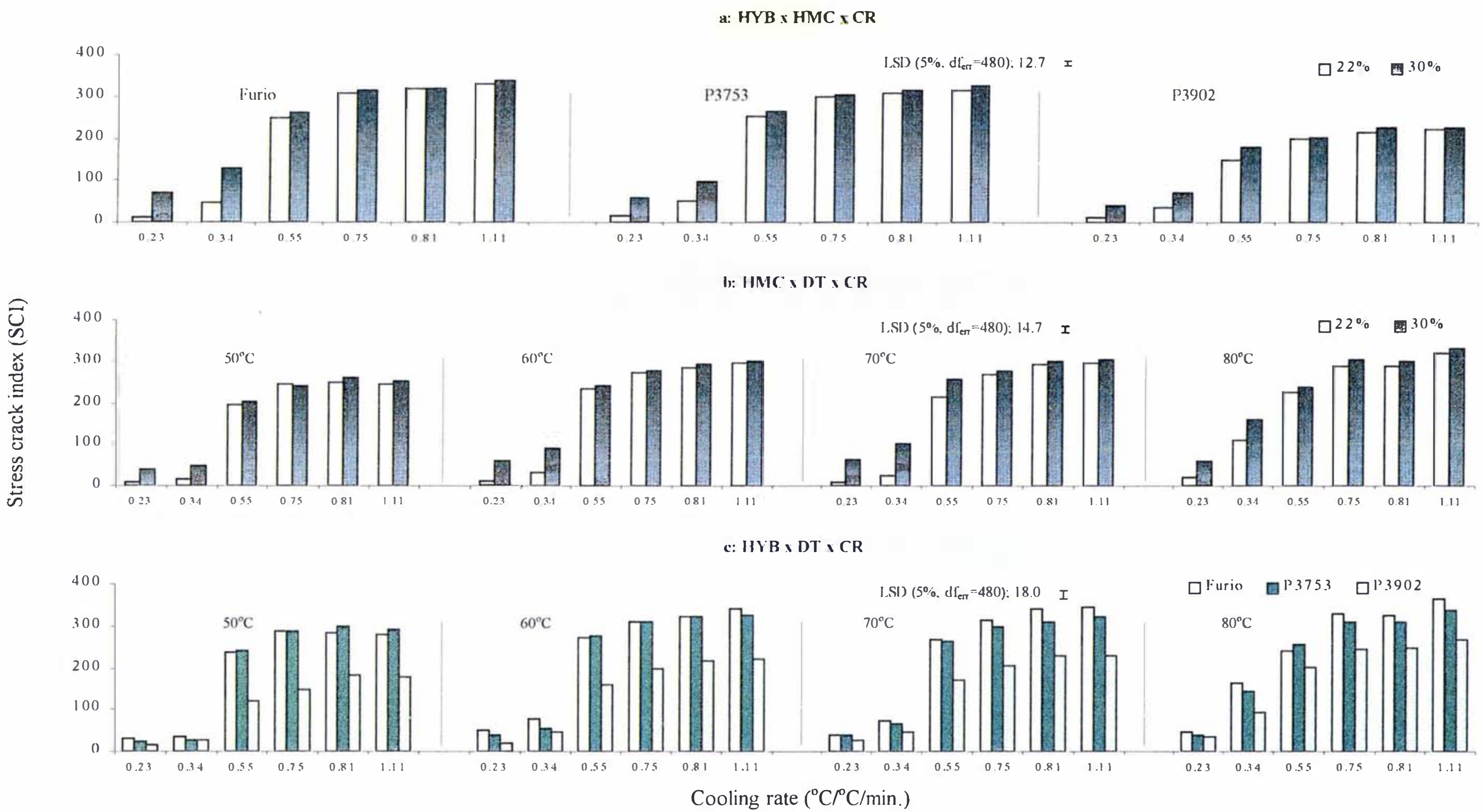


Figure 3-13. Three-way interactions among hybrid, harvest moisture, drying temperature, and cooling rate for stress crack index (SCI).

From the ANOVA table, the F-value for the cooling rate was the greatest (not shown), indicating that the effect of cooling rate on stress cracking and SCI stood out among the main effects. Irrespective of the levels of hybrid, nitrogen, harvest moisture and drying temperature, at the lowest cooling rate of 0.23 (^{o}C/^{o}C/min.)•10^{-2} checking was minimal, and SCI was less than 100 (Table 3-6). In contrast, at higher cooling rates between 0.55 and 1.11 (^{o}C/^{o}C/min.)•10^{-2}, grains had less than 50% non-stress cracking, more than 25% multiple stress cracking, and SCI values of more than 100 regardless of the levels of other variables (Table 3-6, Figure 3-12 and 3-13).

Figure 3-14 shows prediction curves fitting for the over all average of SCI for the three hybrids grown at different levels of applied nitrogen, dried at various drying temperatures and cooled with various cooling rates. The three hybrids all had a similar starting point at the lowest cooling rate of 0.23 (^{o}C/^{o}C/min.)•10^{-2}, but they had different asymptotes.

The predicted SCI of the three hybrids reached a maximum (asymptote) around 0.75 (^{o}C/^{o}C/min.)•10^{-2} cooling rate. At cooling rates between 0.34 to 0.55 (^{o}C/^{o}C/min.)•10^{-2}, the SCI of Furio and P3753 increased sharply, while that of P3902 increased relatively smoothly (Figure 3-14). The hybrid P3902 had a lower predicted maximum SCI than the other two hybrids at both nitrogen treatments (about 200 at 0 kg N/ha and 240 at 230 kg N/ha).

The predicted SCI maximum of Furio and P3753 were similar; about 313 to 343 and 304 to 325 at 0 kg N/ha and 230 kg N/ha, respectively. Increasing nitrogen level from 0 to 230 kg N/ha increased the predicted maximum SCI in all three hybrids, but the difference in maximum SCI between the two nitrogen levels was relatively small (Figure 3-14).

In addition, there was minimal stress cracking, an average of around 95% non-cracked sound grains when grains were dried at 25^{o}C, but drying time was around 24 hours for 22% harvest moisture and 36 to 48 hours for 30% harvest moisture, respectively (data not shown).

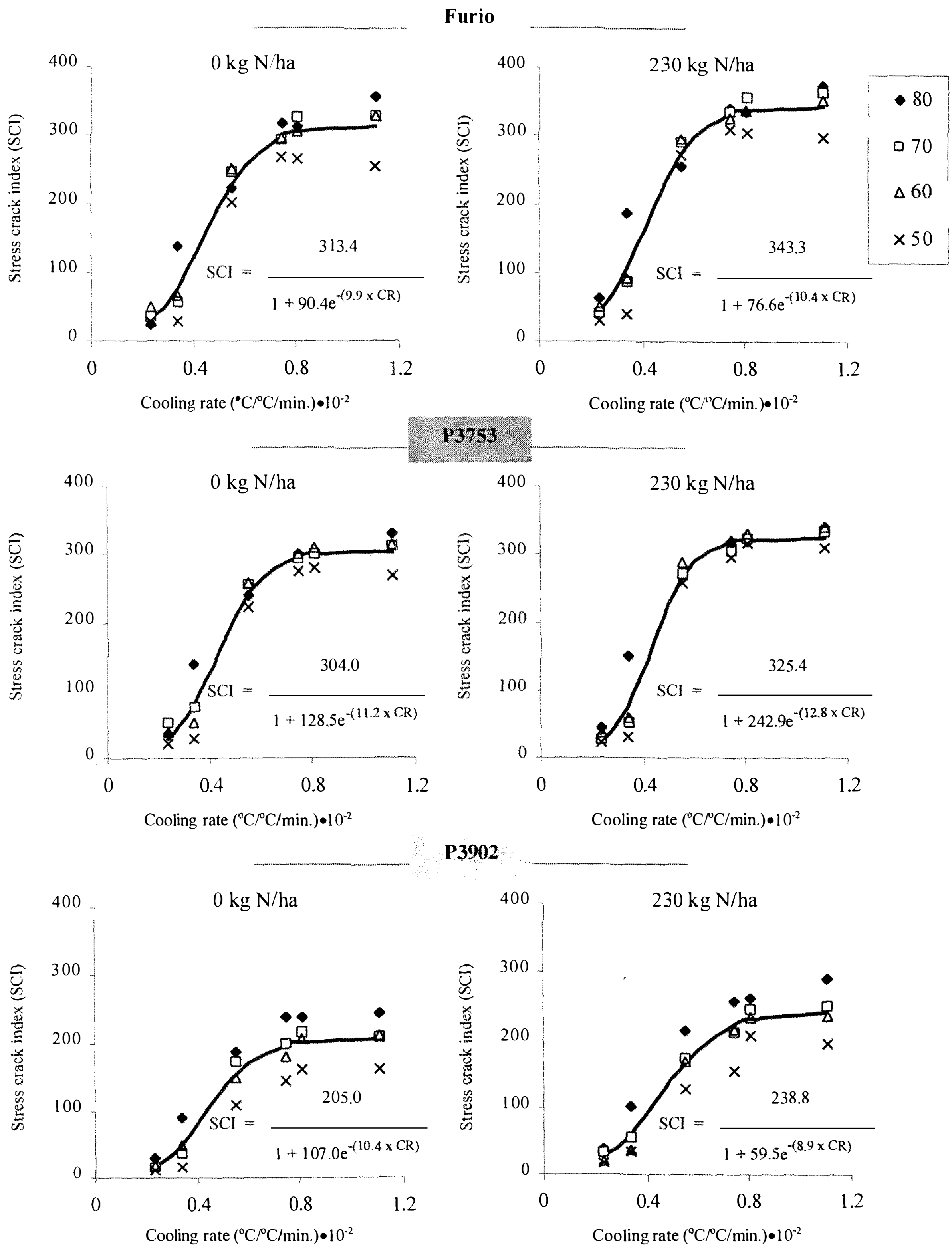


Figure 3-14. Models for stress crack index for three maize hybrids grown at different levels of applied nitrogen, dried at various drying temperatures and cooled at various cooling rates.

Note: The empirical model (a thick solid line) was calculated using the following equation:

$$SCI = \frac{A}{1 + B \bullet e^{-(C \times CR)}}$$

where, A = asymptote, B = constant for initial value of SCI, C = rate increase in SCI to the asymptote within the range of drying air temperature of 50, 60, 70, and 80°C, and CR = cooling rate (°C/°C/min.)$\bullet 10^{-2}$.

3-4. Discussion

In this study, P3902 was the only hybrid that significantly increased in grain weight and hardness ratio (H/S ratio) as nitrogen increased from 0 to 230 kg N/ha (Figure 3-9). While, P3753 (intermediate hard) did not significantly increase in grain hardness and grain weight, probably due to its larger number of grains per cob (Table 3-1 and Figure 3-8). This might be due to the splitting of the side dressing of nitrogen fertilizer during growth (Schreiber et al., 1962), and this also indicates that the three hybrids have different responses to nitrogen (Tsai et al., 1984).

The results also showed that hybrid P3902, which had the highest proportion of H/S ratio, was relatively less sensitive to stress cracking than Furio and P3753 (Table 3-6), indicating that through hybrid selection it might be possible to reduce stress cracking. This result generally agrees with other published data (Weller et al., 1990; Peplinski et al., 1994; Hardacre and Pyke, 1998a).

The main differences among the three hybrids found in this experiment were their sizes/shapes and hardness (H/S ratio) (Table 3-2). However, the effects of specific physical characteristics of hybrids such as size/shape and hardness on stress cracking in maize grains and the relationship among them cannot be conclusive from the results of this experiment.

From the literature it is known that stress cracking in maize grains normally occurs in the protein matrix between starch granules (Balastreire et al., 1982), and thus maize hybrids which have different endosperm characteristics show different stress crack susceptibility. For example, Kirleis and Stroshine (1990) reported that hard maize grains had a higher percentage of stress cracks than soft grains, but hard maize grains had better milling characteristics. The results of this experiment, however, do not agree with their results. For example, there was no significant difference in hardness ratio between P3753 and P3902 at 230 kg N/ha (Figure 3-9), but P3902 had a significantly lower stress cracking percentage than P3753 with elevated drying air temperatures (Table 3-6 and Figure 3-12, 3-13 and 3-14). The unknown structural characteristics of endosperm in maize grains might affect the stress-crack susceptibility.

The hybrid P3902 has a dark yellow colour in its hard endosperm, while P3753 and Furio have a light yellow colour in their hard endosperm and were more translucent than P3902 when grains were candled during stress cracking counting. It is suspected that instead of the amount of hard endosperm (i.e., H/S ratio) in the maize grain, other physical and/or chemical characteristics of maize hard endosperm may affect the susceptibility to stress cracking. Although not measured this experiment, the amounts and properties of starch granules and protein bodies in maize hard endosperm, or structural differences in hard endosperm due to differences in genetic or cultural background may all be involved in stress cracking (Peplinski et al., 1994).

Another important observation in this experiment was the time during which stress cracking developed in grain, and that greater checking in large and round grains rather than small and flat grains was often found during candling. These findings were similar to previous reports (Thompson and Foster, 1963; Zhu and Cao, 1996). Stress cracking in maize grains generally did not begin immediately after drying, although a few fissured lines were found shortly after drying in the over-dried grains which were used for measuring the drying time of maize in the extra drying tray. This could be resulted in longer exposure to a drying temperature (Sarker et al., 1996) and also frequent exposures to ambient temperature during re-weighing. Occasional cooling during re-weighing might affect endosperm viscoelaticity (increase rigidity).

Although the main effects of nitrogen and grain harvest moisture content on stress cracking were significant, they were relatively small (Table 3-6). It has previously been reported that maize harvested at high moisture contents is more susceptible to stress cracking and breakage with high temperature drying (Thompson and Foster, 1963; Peplinski et al., 1975; Moes, and Vyn, 1988; Sarwar, 1988; Weller et al., 1990). Increasing stress cracks in maize grains harvested at high moisture contents might be associated with a greater drying stress due to a greater range of moisture reduction from the maize grain than those harvested at low moisture contents (Moes, and Vyn, 1988).

In this experiment, drying time was largely reduced as harvest moisture reduced from 30% to 22%. However, there was no significant difference in the drying rate of maize grain between the two harvest moisture contents (Table 3-3) and the effect of harvest moisture on stress cracking was relatively small compared to other main effects including hybrid, drying temperature and cooling rate (Table 3-6).

The effect of drying temperature (rate) on stress cracking was significant (Table 3-3 and Table 3-6). However, the effect of drying temperature on stress cracking was far smaller than that of cooling rate (Table 3-6 and Figure 3-14), indicating that the severity of stress cracking in maize grain is more dependent on cooling rate than on drying temperature (rate), for example:

At the lowest cooling rate of 0.23 ($^{o}C/^{o}C/min.)\bullet 10^{-2}$ (45^{o}C-slow cooling (tempering)), checked stress cracking in maize grain was minimal and there was less than about 15% multiple stress cracking, and thus the SCI was less than 100 regardless of the hybrid, or levels of nitrogen, harvest moisture and drying air temperature (Table 3-6 and Figure 3-14).

This indicated that increases in cooling rate due to low temperature and high drying temperatures might increase the moisture and temperature gradients between outer and centre parts of the grain. Thus grains dried at high temperatures and cooled rapidly had greater numbers of multiple or checked stress cracks.

Decreases in cooling rate will relieve the drying stress by allowing moisture loss at a slow rate followed by high temperature drying and moisture and temperature equilibrate through the grain. This is called "tempering" (Brooker et al., 1992).

The effect of drying and cooling rate on stress cracking is summarized in the model developed for SCI (Figure 3-14). The function developed in this study successfully predicted the average value of SCI for hybrid, nitrogen, and drying temperature. However, this model did not fit each SCI value for hybrid, nitrogen, harvest moisture and drying temperature well. In this experiment, grains were dried in a single layer, but not cooled in a single layer; this could be the reason why the model was not fitted well for individual values.

Further work using single layer drying or cooling may allow the development of a good model. However, the effect of grain size/shape on drying rate and stress cracking should also be incorporated into the model.

3-5. Conclusions

The results of this experiment confirmed the predominant effect of slow cooling (tempering) in significantly reducing stress cracking. Other main effects including drying temperature, hybrid, harvest moisture and nitrogen on stress cracking were also significant. The average prediction curve for SCI in this experiment indicated that stress cracking in maize grains could reduce by using a low drying temperature, and by selecting a hybrid less susceptible to stress cracking. However, the effects of harvest moisture and nitrogen on stress cracking were relatively small compared to other main effects. The followings are summary of the results of this experiment:

1. Grain hardness (hard to soft endosperm ratio (H/S ratio)) was significantly affected by the interaction between hybrid and nitrogen. As nitrogen was increased from 0 to 230 kg N/ha, H/S ratio increased by an average of 0.3, 0.6, and 1.5, in Furio, P3753, and P3902, respectively, but only the increase in H/S ratio of P3902 was statistically significant.
2. The effect of drying temperature and harvest moisture on drying time was dominant, while the effect of N was relatively small. Drying rate was also significantly affected by hybrid and drying temperature, but it was not affected by harvest moisture. The drying rate increased exponentially from 23.6 to 77.3 (kg/hr/kg)$\bullet 10^{-3}$ as drying temperature increased from 50 to 80^{o}C. The hybrid P3902 had the slowest drying rate and it was significantly lower than the other two hybrids.
3. The effect of cooling rate on stress cracking and stress crack index (SCI) stood out among the main effects. At the lowest cooling rate of 0.23 (^{o}C/^{o}C/min.)$\bullet 10^{-2}$, checked stress cracking was minimal, and SCI was less than 100 and at higher cooling rates between 0.55 and 1.11 (^{o}C/^{o}C/min.)$\bullet 10^{-2}$, grains had more than 25% multiple stress cracking, regardless of the levels of hybrid, nitrogen, and drying temperature.

4. The predicted SCI of the three hybrids reached a maximum (asymptote) around 0.75 ($^{o}C/^{o}C/min.)\bullet 10^{-2}$ cooling rate. The hybrid P3902 had a lower predicted maximum SCI than the other two hybrids at both nitrogen treatments (about 200 at 0 kg N/ha and 240 at 230 kg N/ha). The predicted SCI maximum of Furio and P3753 were similar; about 313 to 343 and 304 to 325 at 0 kg N/ha and 230 kg N/ha, respectively.

Chapter 4 Effects of grain size, shape, and hardness on drying rate and the occurrence of stress cracks

4-1. Introduction

Maize grains are heterogeneous in their size, shape, and hardness due to different genetic background among hybrids or the placement of the grain on the maize ear within a hybrid (Watson, 1987b; Mannino and Girardin, 1994; Li et al., 1996). This heterogeneity may be explained by competition among grains during grain development, or by increased susceptibility to stress conditions of grains in an unfavorable position on the ear (Daynard and Duncan, 1969; Tollenaar and Daynard, 1978; Mannino and Girardin, 1994).

Due to different grain positions in the maize cob from the tip to the butt, substantial moisture variation in maize grains within a hybrid also exists and it causes non-uniform drying in relation to grain moisture content and stress cracking (Bakker-Arkema et al., 1996; Montross et al., 1999). Montross et al. (1999) reported that maize exiting a high temperature dryer, regardless of the type, had a standard deviation in the moisture content of the individual grains of 3 to 5%, but this decreased to about 1% within three days, and will not change during storage. They also suggested that variation in moisture content in small grains might contribute to this non-uniform drying after high temperature drying. If such grains were exposed to high temperature drying, stress cracking levels might increase and could increase breakage susceptibility and reduce the grain end use value (Fox et al., 1992; Eckhoff and Paulsen, 1996; Paulsen et al., 1996).

In the Chapter 3 experiment, the susceptibility to stress cracking differed among the hybrids. The main differences among the hybrids were in grain size, shape, and hardness ratio (hard to soft endosperm ratio). This indicates that differences in grain size, shape and hardness may affect susceptibility to stress cracking. However the effect of grain size, shape, and hardness on stress cracking and drying rate has not yet been investigated. This information can be useful for understanding the maize grain drying process in practice and also useful for breeding for food maize for a specific end use.

Additionally, the effect of slow cooling or tempering after drying on stress cracking in maize grain is also important, and its benefits have been known for decades, but there is little information about the effect of tempering on maize hybrids that have different hardness characteristics. Therefore the objectives of this study were to study the drying characteristics of four maize hybrids with different physical characteristics, including:

1. to determine the effect of size, shape, and hard/soft endosperm ratio on stress-crack formation in maize grain,
2. to developing the effect of drying temperature on development of stress cracking,
3. to develop an empirical model for the chronological development of stress cracking, and
4. to determine the effect of tempering on stress cracking.

4-2. Materials and Method

4-2-1. Maize hybrids and grain classification

In this study, six different maize hybrids, grown as commercial crops in the Manawatu region, were used. The hybrids, Hmv565-3xE1386, CF06, CF05, and Furio in the 1997 experiment, and Clint and P3902 for the 1998 experiment were selected on the basis of different grain hardness characteristics. All the maize cobs were hand-picked, hand-shelled and grain stored at 5°C before being used.

A. Maize hybrids and grain classification for 1997 experiment

In 1997, around 140 cobs of four hybrids, Hmv565-3xE1386, CF06, CF05, and Furio were picked by hand and hand shelled at 20^{th} of May. Grain moisture content at harvest ranged from 24 to 30%.

Table 4-1 shows classification on size and shape of maize grains from the four hybrids (before drying). Broken and very small grains from the shelled maize (RM) were removed through a 6.75-mm round-hole sieve. Grains were then divided on their ability to pass through and/or over sieves into 6 categories i.e., small round (SR), medium round (MR), large round (LR), small flat (SF), medium flat (MF) and large flat (LF).

Firstly, grain size was determined by using two round-hole sieve diameters (8.73 mm and 9.53 mm). Small grains were passed through 8.73 mm, medium size grains were left over 8.73 mm and passed through 9.53 mm, and large grains were left over 9.53 mm. Grain roundness was then determined by using a 5.95 mm slot-hole sieve (19.05 mm). Flat grains were passed through this slot-hole size, round grains were left over (Table 4-2).

The relative proportions of classified grains were then analyzed using categorical analysis (proc freq; SAS, 1985) to determine whether the proportions (percentage of sample by weight) of grain size and shape differed among hybrids (Table 4-1). Hmv565-3xE1386 had a larger portion of large grains than the other hybrids, while CF05 and CF06 had a higher proportion of small grains. The numbers of round shape grains were substantially less than flat ones in CF05, CF06, and Furio. For these three hybrids the ratio of round: flat was about 20:80, but Hmv565-3xE386 had similar numbers of rounded and flat grains so that the ratio was about 50:50 (Table 4-1).

Table 4-1. Classification on size and shape of maize grains from four hybrids (before drying).

Hole diameter[‡] (mm)	6.75 through	8.73 through	9.53 through and 8.73 over	9.53 over	8.73 through	9.53 through and 8.73 over	9.53 over
Slot thickness (mm)		Round grains 5.95 over			Flat grains 5.95 through		
Shape and size[†]	**RM**	**SR**	**MR**	**LR**	**SF**	**MF**	**LF**
Hybrid			**Percentage of sample by weight (%)[*]**				
Expected[#]	1	8	8	8	30	24	22
Hmv565-3xE1386	0.4	3.2	13.5	27.1	0.4	4.2	51.4
CF06	1.3	10.3	4.1	1.0	48.2	31.6	3.4
CF05	2.1	10.7	6.9	1.3	44.4	27.9	6.7
Furio	1.0	7.1	6.5	4.0	25.2	30.5	25.7

[‡]through = grains were passed through a given hole size, over = grains were not passed and left over a given hole size. All slots 19.05-mm long.
[†]RM= removed from test, SR= small round, MR= medium round, LR= large round, SF= small flat, MF= medium flat, LF= large flat.
[#]The expected percentage of maize grains for each category from statistics of Chi-square.
[*]χ^2-square = 205.8 (P>0.001).

B. Maize hybrids and grain classification for 1998 experiment

In 1998, forty cobs (about 5 kg) of Clint (hard) and P3902 (soft) were hand-harvested at about 20 to 22% grain moisture content. Grains were classified into various sizes and shapes as described above (section A) and stored at 5°C for two weeks before testing.

Clint had a large percentage of large flat and round grains and a smaller percentage of small flat grains than did P3902 (data not shown). Among different sizes and shapes of grains, only medium flat grains were used for the 1998 experiment including stress cracking assessment and tempering treatment.

4-2-2. Physical characteristics of maize grain

A. Moisture content

The AACC air oven method (AACC, 1983) was used for determining maize grain moisture content. From each category of sample (i.e., hybrid and size/shape), 15g of unground sample was dried in open aluminum containers. After drying, the containers were removed, sealed and placed in a desiccator to cool to room temperature. Grain moisture content (wet basis) was then calculated using formula 3.2.

B. Shortest diffusion pathway (SDP)

Shortest diffusion pathway (SDP) was defined as the shortest distance from the centre to the grain surface in the cross-sectioned area of the maize grain (Figure 4-1). To determine the SDP of maize grain, 20 dried grains per replicate (3 replicates) were used. After drying, each grain was sectioned just above the top of the embryo region (about 2/3 from tip cap to crown) using a knife (Figure 4-1) and then the minimum width across the sectioned area (W_m) was measured by hand with a digital caliper. The SDP was then calculated as in equation (4.1):

$$\text{Shortest diffusion pathway (SDP)} = 0.5W_m \qquad \text{------------ (4.1)}$$

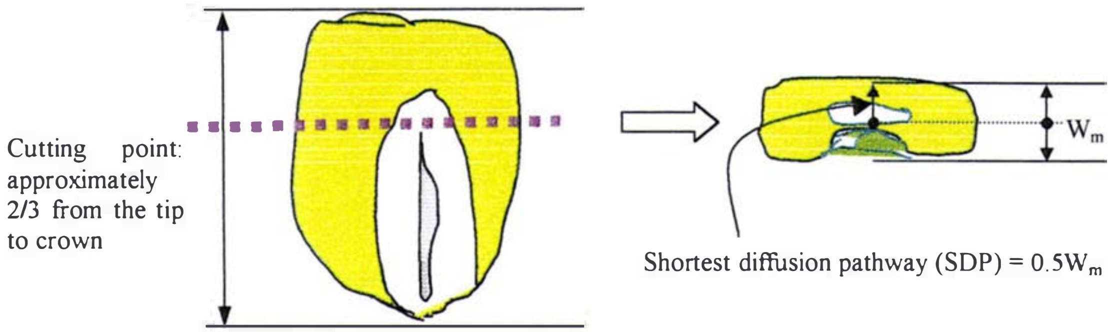


Figure 4-1. Sectioning of maize grain for measuring the shortest diffusion pathway (SDP), W_m is defined as the minimum width across the sectioned area.

C. Comparison of physical characteristics of maize grains for 1997 and 1998 experiment

1) Physical characteristics of six different categories of grains for the four maize hybrids in the 1997 experiment

Table 4-2 presents the different physical characteristics of maize grains in six size and shape categories for the four hybrids used in the 1997 experiment. Initial grain moisture content and shortest diffusion pathway were determined as previously described. Hundred-grain weight and bulk density were determined prior to drying and were adjusted to 14% moisture content, as described in Chapter 3. The individual grain drying rate, length (L_a), width (L_b), thickness (L_c), roundness (R), and hardness ratio (H/S ratio) were determined as described in Chapter3 (section 3-2-4).

Table 4-2. Physical characteristics of different size and shaped grains for four maize hybrids[‡].

		MC (%)	BD (kg/hl)	HGW (g)	L_a (mm)	L_b (mm)	L_c (mm)	R	DR (kg/hr/kg)•10^{-3}	H/S ratio	SDP
Hybrid	Hmv	29.7	72.9	38.5	10.92	8.69	6.13	0.769	30.6	4.8	2.99
	CF06	30.5	70.3	32.1	10.70	8.61	5.70	0.758	44.2	1.9	2.75
	Furio	23.8	68.2	33.9	10.78	8.66	5.86	0.761	48.8	1.4	2.85
	CF05	29.5	68.8	33.3	11.11	8.62	5.87	0.747	41.1	1.2	2.84
Significance		***	***	***	***	**	***	***	***	***	***
LSD (5%, df_{err}=48)		0.1	0.8	0.7	0.16	0.07	0.13	0.010	1.8	0.3	0.07
Size & Shape	MR	28.5	69.7	35.7	9.87	8.38	7.27	0.856	36.8	2.0	3.50
	LR	28.6	71.2	40.7	10.23	9.12	7.13	0.854	33.8	2.0	3.47
	SR	28.0	69.5	30.7	9.30	7.86	6.95	0.860	42.4	1.9	3.38
	MF	28.6	69.6	33.2	12.24	8.79	4.68	0.650	44.4	2.7	2.29
	LF	28.5	70.1	37.8	12.26	9.72	4.72	0.674	39.1	2.6	2.27
	SF	28.1	69.9	28.6	11.36	8.01	4.60	0.659	50.3	2.9	2.25
Significance		***	***	***	***	***	***	***	***	***	***
LSD (5%, df_{err}=48)		0.1	0.8	0.7	0.16	0.07	0.12	0.010	1.8	0.3	0.07
Interactions											
Hybrid x Size & shape		***	*	***	***	***	***	***	***	***	***

[‡]Note: The order for the four hybrids was according to their hardness ratios and the order for size and shape category was according to shortest diffusion pathway (SDP). MC=moisture content of grain after sieving, BD=Bulk density, HGW=Hundred-grain weight, L_a=Length, L_b=Width, L_c=Thickness, R=Roundness, DR=Drying rate, H/S ratio=Hardness ratio, SDP=Shortest diffusion pathway, Hmv=Hmv565-3xE1386, SR=Small round, MR=Medium round LR=Large round, SF=Small flat, MF=Medium flat, LF=Large flat.

NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively.

As shown in Table 4-3, all the physical characteristics of maize grains measured differed significantly among the hybrids and grain size and shape categories; there were also significant interactions between hybrids (HYB) and grain size and shape (S & S) categories.

As seen in Table 4-3, Furio had significantly lower harvest moisture content (around 24%) than the other three hybrids (around 30%). Within grain categories, small grains had significantly lower harvest moisture contents than the large grains (Table 4-3). Nevertheless, within a hybrid, differences in the initial grain moisture contents between the size and shape categories were very small and less than about 1% (Appendix 2).

The flint type hybrid, Hmv565-3xE1386 (hard), had a significantly higher bulk density and hundred-grain weight than the other three hybrids (Table 4-3). CF06 had an intermediate bulk density, but it had a significantly lower hundred-grain weight than the other three hybrids (Table 4-3). Within size/shape category of grain, large round grains had significantly higher bulk density (an average of 71.2 kg/hl) than the other sizes/shapes categories (Table 4-3). The difference in bulk density within size/shape category of grain within a hybrid was small and negligible in terms of practical importance (Appendix 2).

Within the same grain size category, large round grains had the highest hundred-grain weight. In contrast, small flat grains had the lowest hundred-grain weight. Within a hybrid and same shape category, hundred-grain weight increased significantly as grain size increased from small to large and the difference in hundred-grain weight between size categories was about an average of 5g (Table 4-3 and Appendix 2).

Differences in grain dimensions; length, width, thickness and roundness among the hybrids were also significant (Table 4-3). CF05 had the longest grain length and was flattest among the hybrids. Grain thickness and shortest diffusion pathway (SDP) differed significantly among the hybrids in the following order: Hmv565-3xE1386 > CF05 = Furio > CF06. However, the differences in grain dimensions among the four hybrids within a same size/shape of grains were small and practically negligible, compared to those within size/shape category of grains.

Flat grains had significantly greater length and width than round grains within a same size category. On the other hand, round grains had significantly greater thickness and roundness than flat grains; thus round grains had a significantly greater shortest diffusion pathway (SDP) (Appendix 3 and 4). Within a hybrid and a shape category, grain length and width increased linearly as the size of the grain increased from small to large, but the difference in grain length between medium and large flat grains was small (Appendix 3).

The drying rate of individual grains differed significantly among the hybrids in the following order: Furio > CF06 > CF05 > Hmv565-3xE1386 (Table 4-3).

Within size/shape category, small and flat grains had a significantly higher drying rate than large and round grains. The drying rate of small flat grains was highest among the different categories of grains, followed by small round grains. Large round grains had the lowest drying rate among the grain sizes/shapes categories. As shown in Appendix 4, grain drying rate decreased significantly as grain size increased from small to large, but the difference in drying rate was relatively small in flat grains of Hmv565-3xE1386.

Grain hardness ratio (H/S ratio) differed significantly with hybrid in the following order: Hmv565-3xE1386 > CF06 > CF05 = Furio (Table 4-3). Within size/shape category, flat grains had significantly higher hardness ratios than round grains (Table 4-3). However, the difference in the hardness ratio among various sizes/shapes categories of grains within a hybrid was small and negligible in terms of practical importance (Appendix 4).

2) Physical characteristics of medium flat grains of Clint and P3902 in 1998

Table 4-3 presents the physical characteristics of medium flat grains of Clint and P3902. The harvest grain moisture content for the two hybrids was 20.5% for P3902 and 22.2% for Clint, respectively. Clint had a significantly higher grain weight, bulk density and hardness ratio than P3902. Roundness of P3902 was significantly higher than that of Clint due to its shorter length. However there was no significant difference in grain thickness between the hybrids (Table 4-3) and thus SDP (data not shown).

Table 4-3. Comparison of grain moisture content, hundred-grain weight, bulk density, hardness ratio, grain dimension and roundness of medium flat grains of P3902 and Clint (1998).

Hybrid	MC‡ (%)	HGW (g)	BD (kg/hl)	Hardness ratio	L_a (mm)	L_b (mm)	L_c (mm)	R
P3902	20.5	35.4	72.7	1.9	12.07	9.10	4.98	0.679
Clint	22.2	37.5	74.8	3.3	12.53	9.00	4.97	0.659
Significance	**	*	*	**	*	*	NS	*
LSD (5%, df_{err} = 4)	0.3	2.1	1.6	0.8	0.30	0.10	-	0.013

‡ Note: MC = moisture content of grain after sieving, HGW = Hundred-grain weight, BD = Bulk density, L_a = Length, L_b = Width, L_c = Thickness, R = Roundness. HGW and bulk density were adjusted to a grain moisture content of 14% (wet basis).
NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

4-2-3. Stress cracking assessment

Two sets of experiment were carried out for defining chronological development of stress cracking in maize grain. In the 1997 experiment, the effect of grain size/shape and hybrid (hardness) on stress cracking was investigated; and in the 1998 experiment the effect of drying temperature on stress cracking was determined.

A. The effect of size and shape and hybrid on stress cracking (1997 experiment)

In 1997, five-categories of maize grains (i.e., small round, large round, small flat, medium flat, and large flat) were used to determine the effect of size and shape and hybrid on stress cracking development. Because of the limitation of the number of grains (Table 4-1), small flat grains of Hmv565-3xE1386 were not used in this experiment and instead of large round grains in all hybrids, the medium round grains as described in Table 4-1 were used.

A total of 300g of maize grains from each category was used i.e., 3-replicates of 50g for stress crack assessment and the same for measuring the drying time needed to achieve the target grain moisture content. To ensure the required numbers of large round and small flat shapes, the amount of maize grains per hybrid required for all experiments was approximately 18kg (about 120 cobs (around 150g grains per cob) per hybrid).

For each replicate, 50g of grains were dried for approximately one and a half hours at 60°C in a single layer. The metal-mesh-drying trays used were about 10cm (length) x 10cm (width) x 2 cm (height) in size. This drying treatment reduced the moisture content of maize grains to around 15%. Immediately after drying, 60 grains were sampled from the dried grains (opaque (chalky) endosperm grains were excluded when grains were selected at 0 minute after drying) and placed into a metal-mesh tray on the laboratory bench and cooled under ambient conditions (20 ±1 °C, about 65-70% RH) for 72 hours in a single layer.

Stress cracking was assessed using 60-grains from each replicate at 0, 0.5, 1, 1.5, 2, 4, 6, 8, 12, 24, 48, and 72 hours after drying as described in Chapter 3. In this experiment, double stress cracking was added. The fissured lines in maize grains were inspected from both the germ (embryo) side and the opposite side to the germ.

During each stress-crack assessment, an additional 20 grains were removed from the dried sample and the position and types of stress cracks in each grain hand drawn on a sheet of paper: 10-grains for the germ side and 10-grains for the reverse side (Appendix 5). After 72 hours, the dried and cooled samples were poured into an open aluminum foil bag to allow moisture equilibration, and stored for a month under ambient conditions before final assessment of stress cracking.

B. The effect of drying temperature on stress cracking (1998 experiment)

In 1998, three replicates of 60 grains (medium flat) of Clint (hard) and P3902 (soft) were weighed and dried at 60°C, and another three replicates dried at 120°C until the target grain moisture content (15%) was reached. The incidence of stress cracks was assessed using the same procedure described above.

4-2-4. Individual grain drying rate and hardness ratio (1997)

In 1997, from the six grain categories (i.e., small round, medium round, large round, small flat, medium flat, and large flat), 20 grains were selected to determine single grain drying rate and the relationship between the drying rate and grain hardness ratio.

Before drying, the initial moisture content of grains was determined as described in section 4-2-2. The drying air temperature was 60°C. Each grain was numbered (1 to 20) on the grain surface using an indelible pen and weighed before being placed in the drying tray. Each grain was re-weighed to 3-decimal places for determining drying rate every 30minutes until the moisture content reached 11-12%.

The dried grains were then cooled under ambient conditions immediately after drying, sealed in an aluminum foil bag, and stored for four weeks before determining the hardness ratio and grain dimensions. Hardness ratio and grain drying rate were determined using the method described in Chapter 3.

4-2-5. Effects of tempering on stress cracking (1998)

In 1998, medium flat grains of Clint and P3902 (about 0.75kg grain per hybrid) were used for determining the effect of post-drying tempering on stress cracking.

Figure 4-2 presents the procedure for determining the effect of post-drying tempering on stress cracking. For each hybrid and each post-drying treatment, three replicates of 60 maize grains (around 25g per replicate) were weighed and dried at 60°C, and another three replicates dried at 120°C until the target grain moisture content (15%) was reached.

After drying, each of five post-drying treatments was applied to dried maize grains: i) fast cooling at ambient temperature (20 ±1 °C, 65-70% RH) in a single layer (T_0); and tempering at ii) ambient temperature (T_1); iii) 40°C (T_2), iv) 60°C (T_3), and v) 80°C (T_4) for 4 hours before slow cooling for 20 hours (see Chapter 3) and then further cooling for 48 hours at ambient temperature in a single layer (see Chapter 4).

The 60°C (T_3) and 80°C (T_4) tempering treatments were excluded for the sample dried at 60°C. The incidence of stress cracks in maize grain after these treatments was assessed using the same procedure described in Chapter 3.

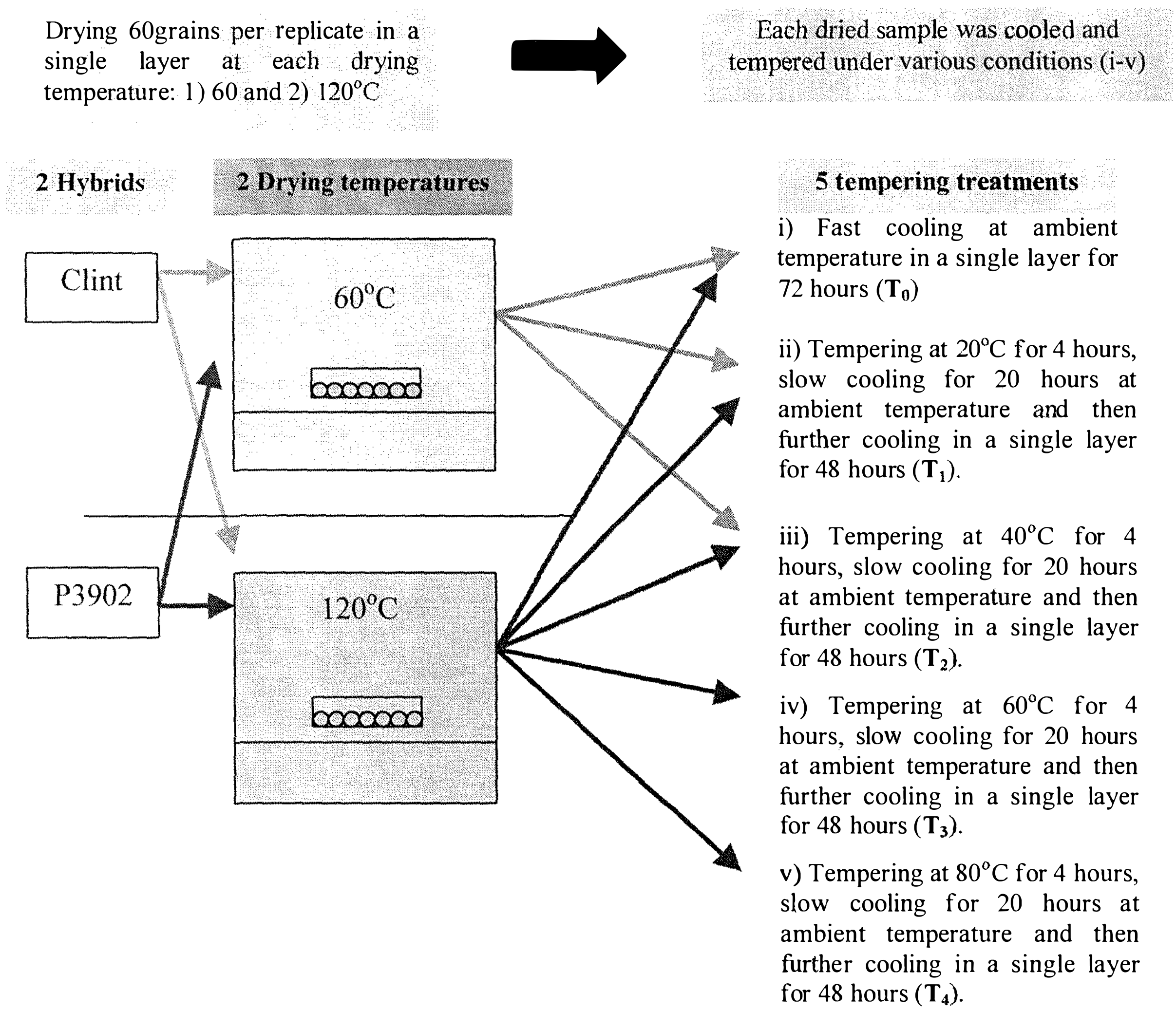


Figure 4-2. Procedure for tempering treatments.

4-2-6. Data analysis and modeling

A factorial arrangement of treatments in a completely randomized design was used to evaluate the effect of hybrid and size and shape categories of maize grain on stress cracking. Data were analyzed by analysis of variance using the general linear models procedure (PROC GLM) of SAS (SAS, 1985). The means of significant main effects were tabulated along with the least significant difference (LSD). Significant interactions between independent variables were presented by plotting the data means on bar-graphs and calculating LSD values appropriate for testing at a significance level of $P < 0.05$. The same procedure was used for analyzing tempering effects on stress cracking.

The observed chronological development of stress cracking in the four hybrids was similar in that many were sigmoidal. Preliminary analysis of the data indicated that the Morgan-Mercer-Flodin (MMF) model (Morgan et al., 1975; Seber and Wild, 1989) predicted the best overall fit to the data. The MMF model (Morgan et al., 1975, equation 4.2) is based on the observation of nutritional responses in higher organisms:

$$y = \frac{\beta\gamma + \alpha x^{\delta}}{\gamma + x^{\delta}} \quad \text{------------------------- (4.2)}$$

where, y = observed response of the organism, α = asymptotic or maximum response of the organism, x = nutrient intake, δ = apparent kinetic order of the response with respect to x as x approaches zero, β = calculated ordinate intercept of the nutrient response curve, γ = nutrition constant (Morgan et al., 1975).

The MMF model was applied to evaluate the development of checked stress cracking in various size and shape categories of maize grain for the four hybrids. Data for each replication of hybrid and size/shape combinations were fitted to a re-parameterized version of this model (Seber and Wild, 1989; Ratkowsky, 1990, equation (4.3)).

$$\text{Checked stress cracking (\%)} = \alpha - \frac{\alpha - \beta}{1 + (\kappa t)^{\delta}} \quad \text{---------------------------- (4.3)}$$

where, α = asymptote, β = intercept, δ = the shape of the sigmoid, and κ = a scale parameter, t = time (hours) after drying as maize grains were cooled at ambient temperature.

In this study, β (intercept) was regarded as zero and thus equation 4.3 was re-written in the following formula (equation (4.4)):

$$\text{Checked stress cracking (\%)} = \alpha \bullet \left(1 - \left(\frac{1}{1 + (\kappa t)^{\delta}} \right) \right) \text{ ------------------------ } (4.4)$$

Of the parameters of the model, α and κ were regarded as being most important in the analysis of the data. α represents the asymptote of the model and κ reflects the rate at which the asymptote is reached. Coefficients of α, κ, and δ from the fitted models were subsequently analyzed by ANOVA.

Standardized multiple stepwise regression analysis was used to determine the relative contribution of hardness ratio (H/S ratio) and grain weight (mg) on single grain drying rate for the different size and shape categories of grain. Raw data were standardized to mean = 0, standard deviation = 1, and the standardized multiple regression performed The regression function for drying rate was given as:

$$\text{Drying rate} = a \cdot (\text{hardness ratio}) + b \cdot (\text{grain weight}) + c \text{ -------- } (4.5)$$

The single grain drying rate was defined as kg of water removal per kg of grain per hour (kg/hour/kg) (Gunasekaran and Paulsen, 1985). The drying rate was determined by the method described in Chapter 3 section 3-2-4 by using each of the single grain drying curve.

4-3. Results

4-3-1. Stress cracking development

A. Effects of hybrid and size and shape on stress cracking (1997 experiment result)

1) Stress cracking in grains 72 hours after drying

Table 4-4 presents stress cracking in grains after drying at 60°C and cooling for 72 hours at ambient temperature. Stress cracking differed significantly among the hybrids and grain size and shape categories.

The hybrid Furio had a significantly higher percentage of checking (83%) and higher SCI, followed by Hmv565-3xE1386 and CF06 (66% checking). CF05 (46% checking) had the lowest checking and SCI. Within size and shape categories, round grains had a significantly higher percentage of checked stress cracking than flat grains. The differences in checking between round and flat grains were about 15 to 30%. Small round grains had about 8% higher checking than large round grains. Checking increased significantly from 50 to 59% as grain size increased from small to large in flat grains (Table 4-4).

The interactions between the hybrids and grain size and shape for stress cracking were significant and are plotted in Figure 4-3. CF05, CF06, and Furio small and large round grains had significantly higher checking and SCI compared to their small and medium flat grains. The differences were especially large between small round grains and small flat grains for CF05 and CF06. Their small round grains had about 40 to 50% more checking than their small flat grains and medium flat grains (Figure 4-3). However the differences in checked stress cracking and SCI were not significant between the large round and the large flat grains in Furio.

Small round grains in CF05 and CF06 had significantly higher checking and SCI than large round grains (Figure 4-3). However there were no significant differences in stress cracking and SCI between small and large round grains in Hmv565-3xE1386 and Furio. Checking in CF05 and Furio increased significantly as size increased from small to large in flat grains, but there were no significant differences in checking and SCI between small and medium flat grains in CF05, CF06 and Furio (Figure 4-3). On the other hand, Hmv565-3xE1386 large flat grains had significantly lower checking and SCI than the other size and shape categories (Figure 4-3).

Table 4-4. The effects of hybrid and size and shape of maize grains on stress crack percentage and stress crack index (SCI) after drying at 60°C and cooling for 72 hours at ambient temperature.

		Stress cracking (%) ‡		SCI†
		Single+Double+Multiple	Checked	
Hybrid (HYB)	Hmv	33.7	66.3	432.5
	CF06	33.3	66.2	429.8
	CF05	51.5	45.9	377.7
	Furio	17.2	82.8	465.3
Significance		***	***	***
LSD (5%, df_{err}=38)		3.6	3.4	7.5
Size and Shape (S & S)	SR	17.1	82.8	463.8
	LR	24.0	75.3	447.1
	SF	48.5	50.9	396.1
	MF	43.5	54.6	400.6
	LF	40.4	59.0	415.0
Significance		***	***	***
LSD (5%, df_{err}=38)		4.0	3.8	8.4
		Interactions		
HYB x S & S		***	***	***

‡ Note: Hmv=Hmv565-3xE1386, SR=Small round, LR=Large round, SF=Small flat, MF=Medium flat, LF=Large flat. Data recorded 72 hours after drying.
† Stress crack index (SCI) was calculated as: SCI = % single + 3 x % multiple + 5 x % checked.
NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

2) Stress cracking development

The types of stress cracking changed with time after drying (Figure 4-4). Single stress cracking, which was normally a vertical-lined fissure in the endosperm at the opposite side of the germ, was first detected 30 minutes after drying (Appendix 5). Very few stress-cracked grains, however, were found immediately after drying when the grain was still hot. Single and non-stress cracked grains as well as double stress cracked grains were present from 30 to 60 minutes after drying (Appendix 5). The double stress cracks were V- or Y-shaped fissured lines mostly found in the germ (embryo) side of the endosperm (Appendix 5). Then, the single and double stress cracks progressed into multiple or checked stress cracks. At the end of counting (72-hour after drying), the majority of the stress cracks were multiple or checked types in all hybrids and size and shape categories of grain, for both the germ side and the opposite side of the grain. Most of the complex fissured lines in flat grains were observed in the crown area of the grain (Appendix 5).

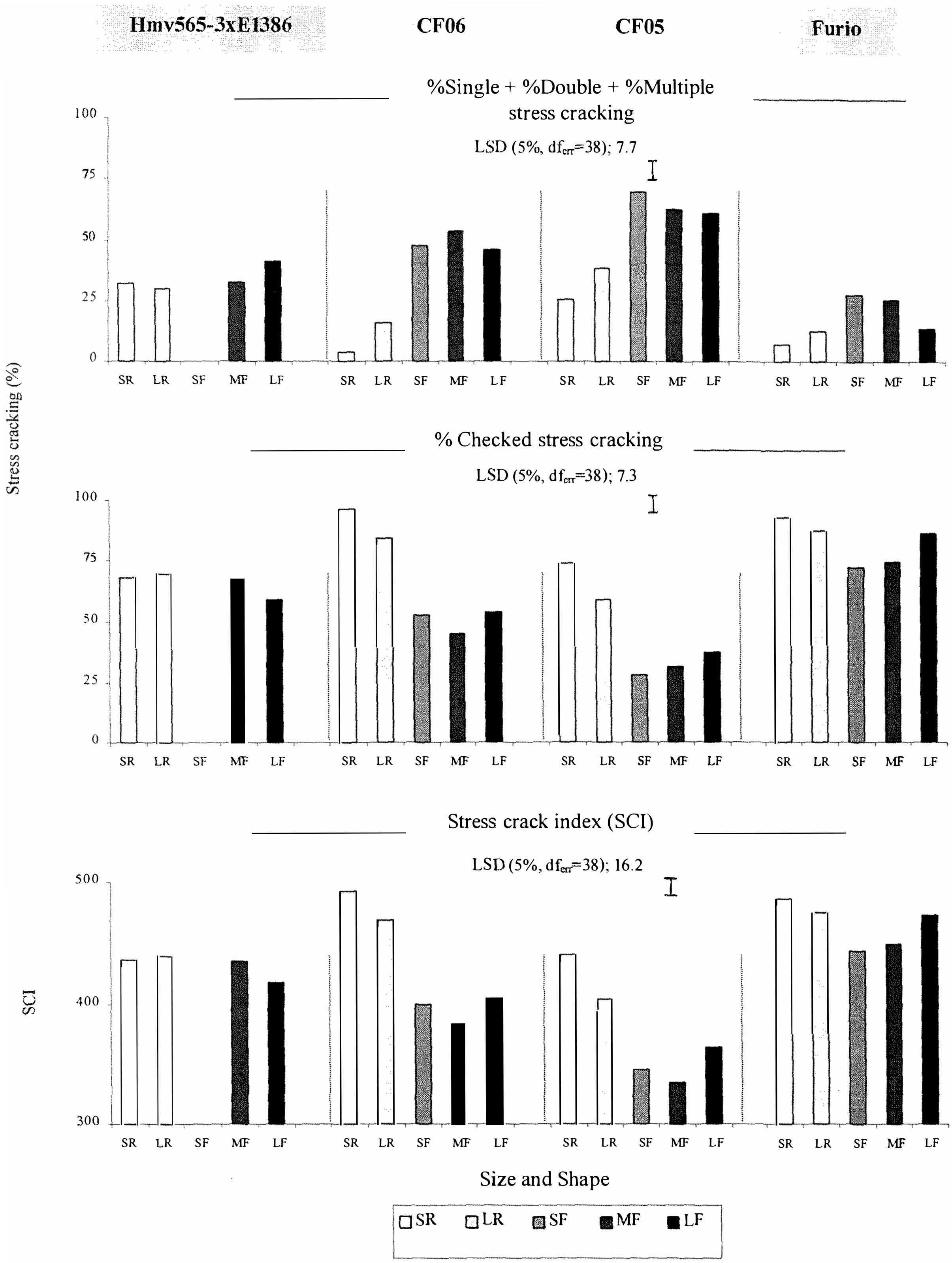


Figure 4-3. The effect of interaction between hybrids and grain size and shape on stress cracking and SCI 72 hours after drying.

Note: SR = small round, MR = medium round, LR = large round, SF = small flat, MF = medium flat, LF = large flat.

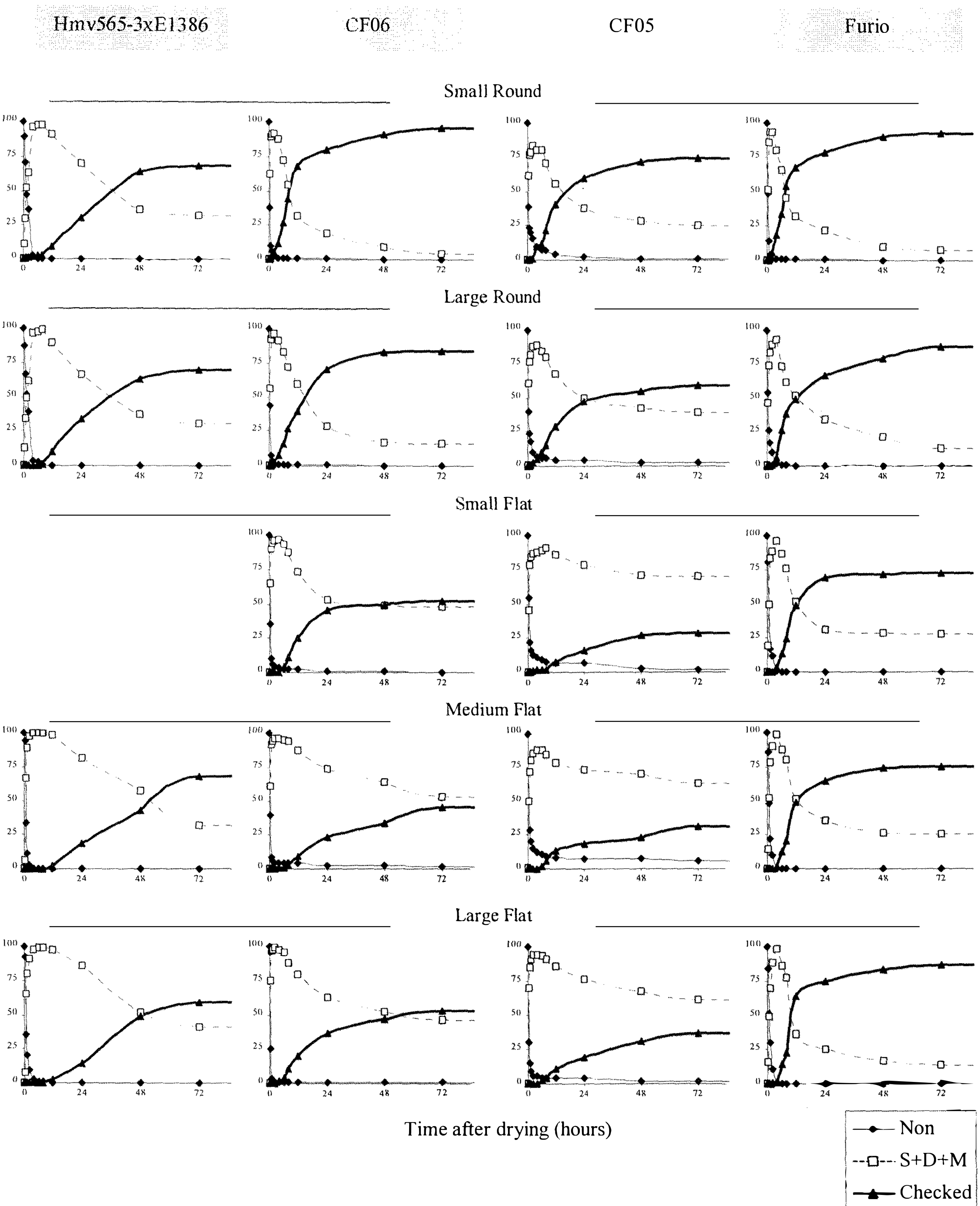


Figure 4-4. Development of stress cracking in various maize grain size and shape categories for four hybrids after drying at 60°C and cooling at ambient temperature for 72 hours.

Note: Non = % non-stress cracking, S+D+M = % single + %double + % multiple stress cracking, Checked = %checked stress cracking. Stress cracking in Hmv565-3xE1386 small flat grains was not measured due to limitation of the number of grains.

The stress cracking in Hmv565-3xE1386 (hard) progressed more slowly than it did for the other three hybrids and some grains of Hmv565-3xE1386 did not develop stress cracking until 2 to 4 hours (large round grains) after drying. Checked stress cracking in Furio and CF06 increased more rapidly than that of the other two hybrids (Appendix 5 and Figure 4-4). The pattern for stress cracking development in CF05 was similar to those of CF06 and Furio, but slower than CF06 and Furio, and CF05 had significantly lower percentages of checked grains at the end of counting (72 hour after drying). The hybrid Hmv565-3xE1386 showed a continuous and linear increase of checked stress cracking from 24 hours after drying to the end of counting, whereas the other hybrids did not change as much (Figure 4-4).

Within size and shape categories, checked stress cracking in round grains developed faster than that in flat grains in every hybrid (Figure 4-4). Round grains of CF06 and Furio started to increase in checking from 4 hours after drying and increased rapidly from 4 to 12 hours after drying (Figure 4-4). Checking, however, was delayed in flat grains of CF06 and Furio (Figure 4-4). There was no change in stress cracking after one month of storage in all the hybrids and size and shape categories of maize grain (data not shown).

3) Comparison of the parameters, α, κ, and δ for the MMF model

In the previous section, the development of stress cracking in the four hybrids and different size and shape was described, but the rate (κ) difference of stress cracking was not evaluated concisely. Morgan-Mercer-Flodin (MMF) function (equation 4.4) parameters were used to quantify and compare the rate and extent of checked stress cracking in various grain size and shape categories for the four hybrids (Table 4-5). This MMF model predicted the real value of checked stress cracking about an average of 95%. In this model, α indicates an asymptote, which represents the predicted highest value of the percentage of checked stress cracking, κ indicates the rate developing checked stress cracking, and δ indicates the curve shape (i.e., the extent of sigmoidal). δ is essential for completion of prediction value and also indicates the development of an asymptote (Seber and Wild, 1989).

Table 4-5. Comparison of the parameters, α, κ, and δ for the MMF model for checked stress cracking in various grain size and shape categories for four hybrids.

		MMF model Parameters for checked stress cracking ‡		
		α	κ	δ
Hybrid (HYB)	Hmv	70.6	0.035	3.1
	CF06	67.4	0.075	2.4
	CF05	47.7	0.061	2.0
	Furio	80.7	0.108	3.0
Significance		***	***	***
LSD (5%, df_{err}=36)		3.41	0.007	0.4
Size and shape (S & S)	SR	83.7	0.094	2.3
	LR	76.6	0.074	2.2
	SF	51.7	0.077	3.0
	MF	51.4	0.063	2.3
	LF	60.2	0.060	3.0
Significance		***	***	**
LSD (5%, df_{err}=36)		3.82	0.008	0.5
		Interactions		
HYB x S & S		***	***	**

‡ Note: Hmv=Hmv565-3xE1386, SR=Small round, MR=Medium round LR=Large round, SF=Small flat, MF=Medium flat, LF=Large flat. Equation for MMF model was (See also section 4-2-6, equation 4.4);

$$\text{Checked stress cracking (\%)} = \alpha \cdot \left(1 - \frac{1}{1 + (\kappa t)^{\delta}} \right)$$

NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

Furio had a significantly higher α (asymptote) followed by CF06 and Hmv565-3xE1386. CF05 had a significantly lower α than the other three hybrids (Table 4-5). Similarly, Furio had the highest κ (rate) followed by CF06 and CF05. Hmv565-3xE1386 had the lowest κ (rate), indicating that checking developed more rapidly in Furio followed by CF06, CF05, and Hmv565-3xE1386 and Furio had more checking at the end of stress-crack counting (72 hours after drying) (Table 4-5).

Within size and shape categories of maize grain, small and rounded grains had significantly higher α and κ than large and flat grains (Table 4-5), indicating that checked stress cracking developed to a greater extent and faster in small and rounded grains than large and flat grains. On the other hand, within flat grains, large flat grains had the highest α. There was no significant difference in α between small and medium flat grains and no significant difference in κ between medium and large flat grains (Table 4-5). There were also significant interactions between hybrids and size/shape of maize grain for α and κ (Table 4-5). However α and κ were predominantly determined by main effects and the interactions were relatively small, when compared to the main effects (Figure 4-4).

The parameter δ, responsible for the shape of the response curve, differed significantly among hybrids and grain size and shape. Higher values of this parameter translate into a more sigmoidal response curve. The hybrids Hmv565-3xE1386 and Furio had significantly higher δ, indicating that they had a stronger sigmoidal response than CF05 and CF06. Similarly, small and large flat grains had had significantly higher δ, indicating that they had a stronger sigmoidal response than rounded grains and medium flat grains.

4) Relationship between physical characteristics and stress cracking

Table 4-6 shows the correlations between grain physical characteristics and the MMF model (equation 4.4) parameters represented in Figure 4-4. Among the MMF parameters, δ (a parameter for curve shape) was regarded as a less important factor for predicting value of percentage checked stress cracking (Section 4-2-6), thus only α (asymptote) and κ (rate) were used for correlating with grain size, shape, and hardness factors.

Table 4-6. Correlations between grain physical characteristics and the MMF model parameters.

MMF parameters	BD (kg/hl)	HGW (g)	L_a (mm)	L_b (mm)	L_c (mm)	R	DR (kg/hr/kg)•10^{-3}	H/S ratio	SDP
α (Asymptote)	0.028	0.079	-0.707	-0.268	0.620	0.703	-0.023	-0.070	0.627
Significance	NS	NS	***	NS	***	***	NS	NS	***
κ (rate)	-0.564	-0.360	-0.424	-0.357	0.203	0.285	0.551	-0.611	0.208
Significance	***	**	**	**	NS	*	***	***	NS

†Note: BD=Bulk density, HGW=Hundred-grain weight, L_a=Length, L_b=Width, L_c=Thickness, R=Roundness, DR=Drying rate, H/S ratio=Hardness ratio, SDP=Shortest diffusion pathway
NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively.

The MMF parameters of α and κ were significantly correlated with several physical characteristics of maize grain (Table 4-6). The α (asymptote) was positively correlated ($r > 0.6$) with shortest diffusion pathway (SDP), thickness (L_c) and roundness (R); while it was negatively correlated ($r > 0.7$) with length (L_a). This indicates that the extent of checked stress cracking in grains increased as SDP and roundness increase, and as grain length decreases.

The κ (rate) was positively correlated ($r > 0.5$) with drying rate; while it was negatively correlated ($r > 0.5$) with hardness ratio and bulk density and, to a lesser extent ($r > 0.35$), hundred-grain weight, length (L_a) and width (L_b) (Table 4-6). This indicates that the checking in grains developed faster as grain drying rate increased. This also indicated that: the smaller the size (or weight) of grain and the lower the hardness ratio of grain, the faster the checking in maize developed.

B. The effect of drying temperature on stress cracking (1998 experiment result)

1) Stress cracking in grains 72 hours after drying

Table 4-7 presents the percentage of stress cracking and SCI of two maize hybrids after drying at 60°C and 120°C and cooling at ambient temperature (20±1°C, 65 to 70% RH).

Stress cracking differed with hybrid and drying temperature. Clint (hard) had significantly higher checking and SCI after drying at 60 and 120°C and cooling at ambient temperature for 72 hours after drying. Checking (%) was nearly doubled as drying temperature increased from 60 to 120°C (Table 4-7). However, there was a significant interaction between hybrid and drying temperature for stress cracking and SCI (Table 4-7).

Figure 4-5 shows the interaction between hybrid and drying temperature for stress cracking in maize grain. Clint had about 75% checking, while P3902 had only about 25% checking after drying at 60°C. As drying temperature increased from 60 to 120°C, P3902 significantly increased in checking and the difference in percentage checking between the two hybrids was small.

Table 4-7. The percentage of stress cracking and SCI of two maize hybrids after drying at 60°C and 120°C and cooling at ambient temperature (20±1°C, 65 to 70% RH) in a single layer (1998 experiment).

		Stress cracking (%)			
		Non	S+D+M	Checked	SCI ‡
Hybrid (HYB)	P3902	1.1	38.4	60.5	416.1
	Clint	0.0	13.0	87.0	473.9
Significance		**	***	***	***
LSD (5%, df_{err} = 8)		0.7	5.5	5.7	14.8
Drying Temperature (DT)	60°C	0.3	47.8	51.9	401.4
	120°C	0.8	3.6	95.6	488.6
Significance		NS	***	***	***
LSD (5%, df_{err} = 8)		-	5.5	5.7	14.8
Interactions					
HYB x DT		NS	***	***	**

‡ S+D+M = %Single + %Double + %Multiple, SCI (Stress Crack Index) = % single + 3 x (% double + % Multiple) +5 x % Checked. Stress cracking was counted 72 hours after drying. NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

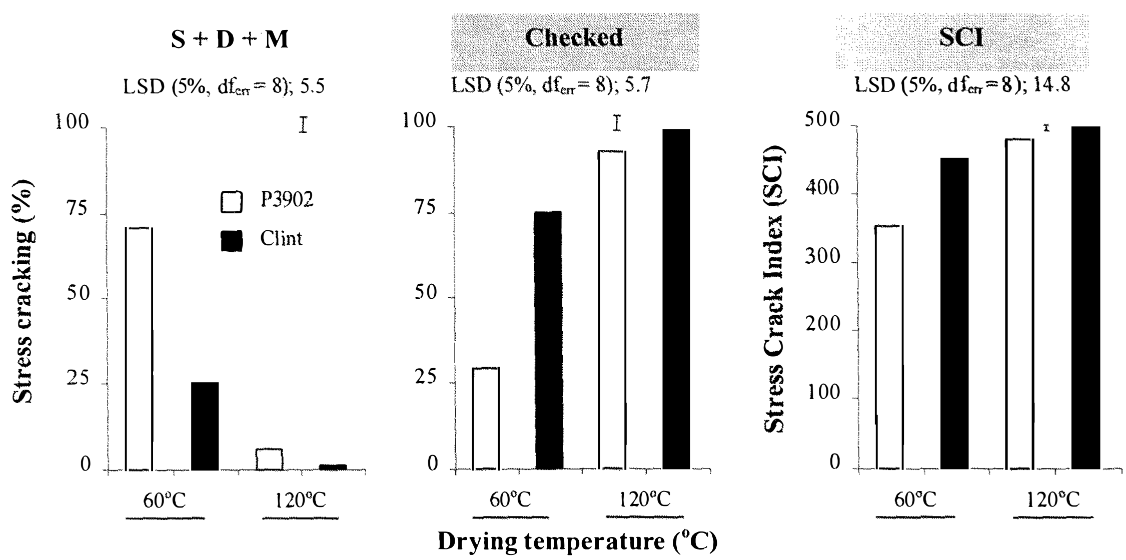


Figure 4-5. The interaction between hybrid and drying temperature for stress cracking in maize grain.

Note: S+D+M = %Single + %Double + %Multiple.

2) The MMF model parameters for stress cracking development

Figure 4-6 shows the chronological development of checked stress cracking in maize grain after drying at 60 and 120°C and cooling at ambient temperature for 72 hours in a single layer. This was also fitted to the MMF model (equation 4.4) and the parameters were used to evaluate the rate and the extent of stress cracking for the two hybrids between the two drying temperatures, 60 and 120°C (Table 4-8).

As seen in Table 4-8, α and κ were significantly differed with hybrid, indicated that the rate and extent of percentage checking significantly differed with hybrid. Clint (hard) had a significantly higher asymptote (α) and rate of increase in checked stress cracking times after drying (κ) than P3902 (soft), indicating that Clint had significantly more checking at the end of cooling and a significantly more rapid increase in checking than P3902. The asymptote (α) was also significantly affected by drying temperature, indicating that the percentage of checked stress cracked grains was significantly higher at 120°C drying than at 60°C drying. Checking at 120°C was nearly double that at 60°C.

The interaction between maize hybrid and drying temperature for the asymptote (α) of checking was also significant (Table 4-8 and Figure 4-6). Clint had about 50% higher checking than P3902 at 60°C drying, but checking in P3902 significantly increased as drying temperature increased from 60 to 120°C and the two hybrids had similar asymptotes around 90 to 99% of checking at 120°C (Figure 4-6).

The rate of increase in checking (κ) did not differ significantly with drying temperature; however the curve shape (δ) was significantly affected by drying temperature (Table 4-8 and Figure 4-9). The parameter δ was nearly doubled as drying temperature increased from 60 to 120°C, indicating that the regression curve for the checking development times after drying at 120°C drying was more sigmoidal than that after 60°C drying (Figure 4-6). This also indicated that checking in grain developed more after drying at higher temperature within the same duration at the same cooling rate condition. The checking increased to a larger amount after 120°C drying than after 60°C drying within the same duration, especially from 0 hour to 24 hours after drying (Figure 4-6).

Table 4-8. Comparison of the parameters, α, κ, and δ for the MMF model for checked stress cracking in maize grain for two hybrids.

		MMF model Parameters for checked stress cracking ‡		
		α	κ	δ
Hybrid (HYB)	P3902	59.3	0.059	3.2
	Clint	87.2	0.091	3.1
Significance		***	**	NS
LSD (5%, df_{err} = 8)		7.4	0.016	-
Drying temperature (DT)	60°C	51.4	0.071	2.4
	120°C	95.1	0.079	3.9
Significance		***	NS	**
LSD (5%, df_{err} = 8)		7.4	-	0.7
		Interactions		
HYB x DT		**	NS	NS

‡Note: The MMF model was (See also section 4-2-6, equation 4.4);

$$\text{Checked stress cracking (\%)} = \alpha \cdot \left(1 - \frac{1}{1 + (\kappa t)^{\delta}}\right)$$

NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively

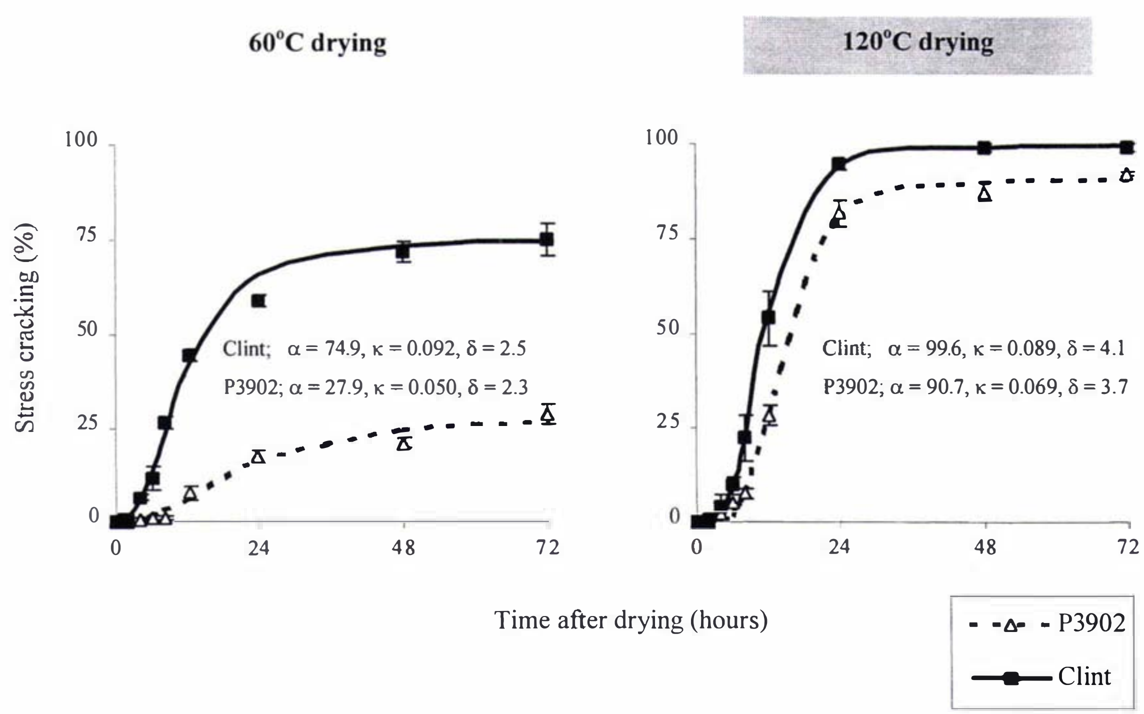


Figure 4-6. Development of checked stress cracking in maize grain after drying at 60°C and 120°C and cooling at ambient temperature for 72 hours (the percentage checked stress cracking data were fitted to the MMF model (Seber and Wild, 1989, equation 4.4).

4-3-2. Relationship between single grain drying rate, grain weight and hardness ratio

Table 4-9 summarizes the standardized regression coefficients for hardness ratio, grain weight, and intercept, respectively. The fitted models accounted from 65 to 74% of the variation in single grain drying rate.

The drying rate for various size and shape categories of grain decreased as unit hardness ratio and grain weight increased. Small grains had similar coefficients for hardness ratio and grain weight. The standardized coefficients for small grain weight were nearly twice as large as that for hardness ratio, indicating that the drying rates for small grains were affected more by grain weight than by hardness ratio. Similarly, the standardized regression coefficients for grain weight for small to large flat grains were higher than that for hardness ratio, suggesting that drying rates for flat grains were also more affected by grain weight than by hardness ratio. However the standardized coefficients for hardness ratio were higher than those for grain weight as grain size increased from small to large in rounded grains. Thus the grain drying rates for medium and large round grains were more affected by hardness ratio than grain weight.

Table 4-9. Single grain drying rate as a function of grain weight and hardness ratio.

Size and shape category	**Standardized Regression coefficients**‡			
	a ± SE (hardness ratio)	b ± SE (grain weight) (mg)	c ± SE (intercept)	R^2
Large round (LR)	-5.61 ± 0.39	-2.52 ± 0.40	35.00 ± 0.49	0.65***
Large flat (LF)	-3.99 ± 0.34	-4.38 ± 0.46	43.45 ± 0.47	0.66***
Medium round (MR)	-6.61 ± 0.37	-3.60 ± 0.54	36.09 ± 0.31	0.74***
Medium flat (MF)	-4.63 ± 0.41	-8.17 ± 0.81	45.87 ± 0.40	0.69***
Small round (SR)	-6.59 ± 0.60	-11.34 ± 1.00	30.16 ± 0.98	0.65***
Small flat (SF)	-5.63 ± 0.55	-9.80 ± 1.08	41.59 ± 1.36	0.72***

‡Note: The order for size and shape category was based on hundred-grain weight presented in table 4-2. SE = standard error. The standardized multiple regression model for single grain drying rate was (see also section 4-2-6):

Drying rate (DR) = a•(hardness ratio) + b•(grain weight (mg)) + c (intercept)

NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively.

4-3-3. The effect of tempering on stress crack reduction in maize grain

Table 4-10 presents the effect of post-drying treatment (tempering) on stress cracking in maize grain. The main effects of hybrid and post-drying tempering treatment (PDT) on stress cracking were significant.

The hybrid P3902 had significantly lower percentage of multiple and checked stress cracking 72 hours after drying at 60°C and 120°C. Increases in tempering temperature significantly reduced stress cracking in maize grain irrespective of drying temperature. Tempering grain at 80°C (T_4) resulted in few stress-cracked grains in both Clint and P3902 after drying at 120°C. However, there were significant interactions between hybrid (HYB) and post-drying treatments (PDT) for stress cracking both at 60°C and 120°C drying (Figure 4-7).

Table 4-10. The effect of post-drying treatments (tempering) on percentage stress cracking in various maize hybrids drying at 60 and 120°C.

		Stress cracking (%)						
		60°C Drying				**120°C Drying**		
		Non	S+D+M	Checked		Non	S+D+M	Checked
Hybrid	P3902	8.4	82.0	9.6		40.8	38.1	21.1
(HYB)	Clint	0.2	54.5	45.3		28.4	27.9	43.7
Significance		*	***	***		***	***	***
LSD (5%, df_{err}=12)		7.4	9.0	5.3	LSD (5%, df_{err}=20)	1.7	3.4	3.2
Post-drying	T_0	0.3	47.8	51.9		0.8	3.6	95.6
Treatments	T_1	0.5	76.1	23.4		0.5	58.7	40.8
(PDT)	T_2	12.1	80.9	7.0		5.8	68.6	25.6
	T_3	+	+	+		71.6	28.4	0.0
	T_4	+	+	+		94.4	5.6	0.0
Significance		*	***	***		***	***	***
LSD (5%, df_{err}=12)		9.0	11.0	6.6	LSD (5%, df_{err}=20)	2.7	5.4	5.1
				Interactions				
HYB x PDT		*	**	**		***	***	***

†Note: S+D+M = %Single + %Double + %Multiple, T_0=fast cooling at ambient temperature (20±1°C, 65-70% RH) in single layer, T_1=tempering at ambient temperature, T_2=tempering at 40°C, T_3 =tempering at 60°C, T_4 =tempering at 80°C, respectively (each tempering treatment was for 4 hours). NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively. + = not measured.

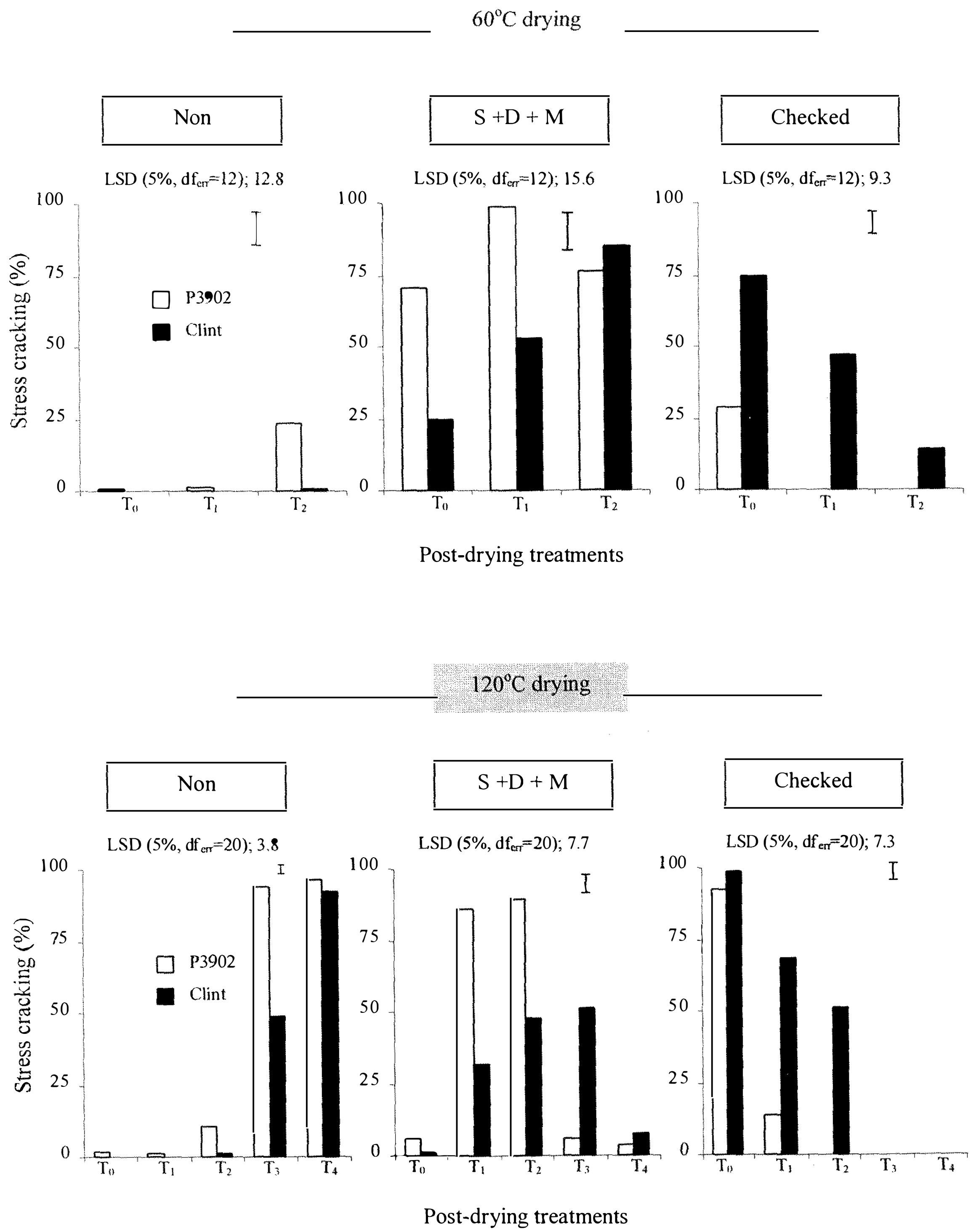


Figure 4-7. The interaction between hybrid (HYB) and post-drying treatments (tempering) for stress cracking in maize grain.

Note: S+D+M = %Single + %Double + %Multiple, T_0=fast cooling at ambient temperature (20±1°C, 65-70% RH) in single layer, T_1=tempering at ambient temperature, T_2=tempering at 40°C, T_3 =tempering at 60°C, T_4=tempering at 80°C, respectively (each tempering treatment was for 4 hours).

Stress cracking in P3902 (soft) was reduced significantly after tempering and ambient slow cooling (T_l) after drying at both 60 and 120°C. At 120°C drying, the percentage of non-stress-cracked grains in P3902 dramatically increased after tempering at 80°C. More than 90% of grains did not have stress cracking in P3902 after 120°C drying and tempering at both 60°C and 80°C (Figure 4-7).

However the effect of tempering on stress cracking in Clint (hard) was small. Clint dried at 120°C had significantly fewer non-stress-cracked grains than P3902 dried at 120°C after tempering at 60°C. In addition, both hybrids dried at 60°C had significantly lower checking than those dried at 120°C and given the same tempering conditions or fast cooling at ambient temperature (Figure 4-7).

4-4. Discussion

Stress cracks in maize grains were not found until drying had ceased. Single or double stress cracking was found shortly after drying and most of the grains had checked stress cracking at the end of counting (72 hours after drying) (Appendix 5). This observation of development of stress cracking agreed with previous reports (White et al., 1982; Sarwar, 1988; Zhu and Cao, 1996).

As expected, the rate and extent of stress cracking in maize grains differed significantly with grain size/shape and hardness ratio (H/S ratio) (Table 4-4 and 4-5 and Figure 4-3 and 4-4). The MMF model (equation 4.4) successfully predicted the real value of the percentage of checked stress cracking (more than 95%) and this provided a more precise interpretation for the rate and extent of stress cracking among different size, shape, and hardness (H/S ratio) of grains for the four hybrids (Table 4-5).

Based on the comparison of the grain physical characteristics (Table 4-2) and the correlations between the parameters and grain physical characteristics (Table 4-6), a possible generalization was suggested for the relationship between stress cracking (rate and extent) and different size, shape and hardness of grains. As seen in Figure 4-8, the extent of stress cracking was more likely affected by shape factors (e.g., SDP), while the rate increase for checking was closely related with grain size factors (e.g., grain weight) and hardness ratio (H/S ratio).

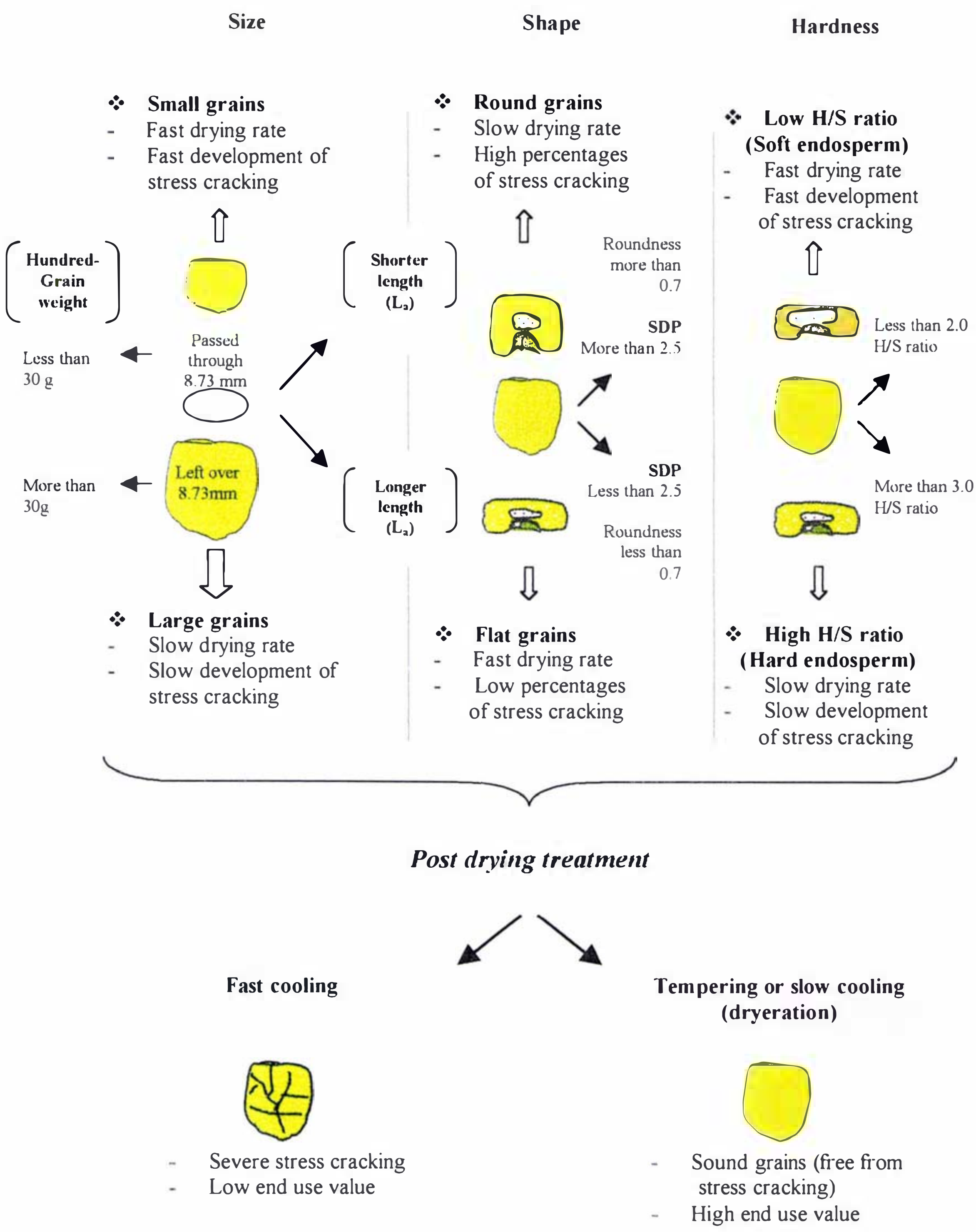


Figure 4-8. Stress cracking and drying rate of maize grain in relation to grain size/shape and the effect of post-drying treatments (dryeration (i.e., tempering)) on reduction of stress cracking.

Grain shape factors including roundness (r = 703), thickness (L_c; r = 0.620) and shortest diffusion pathway (SDP; r = 0.627) were positively correlated with α (asymptote) (Table 4-6). This indicated that the rounder the grain shape (i.e., the greater the SDP), the higher the percentage of stress cracking in grain. This result agrees with Thompson and Foster (1963).

Unfortunately, there was little literature to explain about the reason why the percentage stress cracking increased as the SDP in grains. The extent of stress cracking in a grain could reflect the amount of stress built in the grain during drying and cooling unless the grain had any damage before and after drying. On this basis, a possible assumption for the relationship between the extent of stress cracking and the SDP in grain could be suggested that:

Increases in the SDP in the grain within a size and a hardness ratio (hybrid) might cause to increase the amount of stress (e.g., increases in the moisture and temperature gradients) built in the grain during drying and cooling. Therefore the greater the SDP in grains, the more the stress built in grains and the more stress cracking.

This result also suggested that the SDP measurement could be useful for predicting the extent of stress cracking in maize during postharvest drying.

The negative correlation coefficients for size and hardness factors including hundred-grain weight (HGW), length (L_a), width (L_b), bulk density and hardness ratio with MMF parameter κ (rate) (Table 4-6) indicates that small and soft grains have faster development of stress cracking than large and hard grains.

On the other hand, P3902 (soft) had a significantly lesser extent (α) and rate (κ) of stress cracking than Clint at 60°C and 120°C drying in the 1998 experiment (Table 4-8 and Figure 4-6). This exception makes it difficult to generalize the relationship between grain hardness ratio and stress cracking development. It is thus suspected that susceptibility to stress cracking might be dependent on hard endosperm characteristics rather than simply on its amount in the grain.

Among the size and shape factors, only length (L_a) was linked with both α (asymptote; r = -0.707) and κ (rate; r = -0.424) (Table 4-6). The negative correlation coefficient for length and the MMF parameters indicated that the smaller the grain length; 1) the higher the rate increase in checking and 2) the higher the percentage of checked stress cracking. For example:

Small round grains (shorter length) were more susceptible to stress cracking (Table 4-4 and 4-5). Small round grains had significantly greater value of α (asymptote) and κ (rate), indicating that stress cracking in small round grains developed faster and reached the highest maximum value among different size and shape of grains.

Small round (soft) grains had a larger variation in drying rate due to their variation in hard and soft endosperm ratio (H/S ratio) (Li et al., 1996) or due to variation in moisture content due to their position in the cob (Bakker-Arkema et al., 1996; Montross et al., 1999). Small round grains were found at a similar ratio from the top to the bottom position in the cob in soft and intermediate hybrids (Appendix 6).

The standardized multiple regression for predicting single grain drying rate according to grain weight and H/S ratio (Table 4-9) could support the variations in hard to soft endosperm ratio (e.g., hard and soft endosperm distribution variation) in small grains (less than 30.0g of hundred-grain weight). In the standardized multiple regression, the coefficients for grain weight for drying rates in small grains were twice as large as those for H/S ratio, while the relative contribution of the H/S ratio increased as grain size (weight) increased (Table 4-9).

The variation in H/S ratio in small grains might also contribute to the greater coefficient of variation (CV) for the H/S ratio (11.4%) among different sizes/shapes of the four hybrids (Table 4-2). Thus H/S ratio measurement might not be a good indicator of the differences in grain hardness among maize hybrids (Li et al., 1996), particularly which have large portion of soft grains.

Therefore, when selecting a hybrid for a specific end use, the effects of variation in grain size and shape within a hybrid on the production of high quality end-products should be considered. From the results of this experiment, removing small and rounded grains could reduce checked stress cracking by up to 40 to 50% in soft and intermediate hard hybrids (CF05 and CF06) (Figure 4-3).

However stress cracking, regardless of size/shape and hardness categories of grain, can not be reduced if grains are cooled rapidly with low temperature air after high temperature drying (Table 4-10 and Figure 4-8). Thus dryeration (tempering) is necessary to reduce stress cracking, and its benefits have long been noted (Sarwar et al., 1989). In addition, the results of this experiment found that the higher the drying-temperature, the higher the tempering-temperature required for reduction of stress cracking (Table 4-10 and Figure 4-7). This indicated that instead of drying temperature, cooling rate is the most important factor for maintaining maize quality in relation to reduction of stress cracking in grains.

4-5. Conclusions

The MMF model successfully predicted the rate and the extent of checked stress cracking in various sizes, shapes and hardness ratios of maize grains. The correlations between grain size, shape, and hardness factors and the MMF function parameters also provided a possible interpretation of the rate and extent of stress cracking among different grain size, shape, and hardness, and this made possible the following conclusions:

1. The rounder the grain shape (i.e., greater the SDP), the higher the percentage of stress cracking in maize grain, and the smaller the grain size (i.e., weight and length), the faster the development of stress cracking after high temperature drying,
2. The standardized multiple regression for single grain drying rate according to H/S ratio and grain weight accounted for from 65 to 74% of the variation. The coefficients for various sizes/shapes of grains indicated that the drying rates for small grains were affected more by grain weight than hardness ratio.
3. Tempering grain at high temperatures resulted in few stress-cracked grains in both Clint and P3902. Stress cracking in P3902 (soft) reduced significantly after tempering following drying at both 60 and 120°C, while the effect of tempering on stress cracking in Clint (hard) was small.

Chapter 5 Development of a grain breakage susceptibility tester and a study of the effects of maize grain temperature on breakage susceptibility

5-1. Introduction

Breakage susceptibility is the most important physical and mechanical properties that can determine the usage and value of maize (Watson, 1987a). Increases in grain breakage due to conventional high temperature drying increase broken maize and fine material during subsequent handling, and lowers the end use quality (Watson, 1987a).

Because of the importance of breakage, a number of breakage testers have been developed. Among them, Stein breakage tester (SBT) (Miller et al., 1979, 1981a, 1981b; Watson et al., 1986) and Wisconsin breakage tester (WBT) (Singh and Finner, 1983) have been recommended as the standard device for measuring grain breakage (See Chapter 2 section 2-4-2. E).

The breakage susceptibility of maize grain, however, is moisture dependent (Herum and Blaisdell, 1981; Paulsen, 1983). Thus it has been recommended that the moisture content of the sample (around 12-13%) should be consistent and reported along with the percentage breakage when grain is tested (Miller et al., 1981b). On the other hand, the grain temperature has been noted as a minor factor that affects grain breakage at the time of testing. Herum and Blaisdell (1981) found that breakage susceptibility increased greatly as moisture content decreased from 14 to 12% and increased slightly as grain temperature decreased from 38 to 4°C.

From the literature, standard breakage testers are available and the several grain physical factors related to breakage susceptibility including grain moisture content and grain temperature have been studied (Herum and Blaisdell, 1981; Miller et al., 1981b; Watson et al., 1993). However the effects of high grain temperatures (higher than 40°C) on breakage susceptibility have not yet been studied and data for the chronological change of physical characteristics of maize grain after high temperature drying are not available. This is crucial for understanding the viscoelastic characteristics (i.e., hardness) of the grain in relation to high temperature drying and is also important information for measurement of grain hardness and breakage susceptibility.

In this experiment, a new impact drop tester (Model HT-I drop tester) (Figure 5-1, Plate 5-1, and Appendix 7) was developed for determining the breakage susceptibility of individual maize grains at various grain temperatures and the chronological development of breakage in maize grain. The objectives of the study were to:

1. determine grain breakage at various grain temperatures;

2. measure grain breakage at various times after drying; and,

3. develop an empirical model for grain breakage at various grain temperature and times after drying.

5-2. Material and Methods

5-2-1. Development of the HT-I drop tester

To measure the breakage of an individual grain at high grain temperatures, a new breakage tester (Model HT-I drop tester) was developed. This device consists of five main parts as seen in Figure 5-1, and the detailed structure of each part is presented in Appendix 7. The length of the aluminum steel bar is 588 mm and the radius is 13 mm. The steel tube has holes from 5 cm to 50 cm at 5 cm intervals and the drop-height of the steel bar is manually controlled by the pin inserted in the hole in the middle of the mild steel tube. The steel tube is fixed to a stand with clamps (Figure 5-1, Plate 5-1 and Plate 5-2). The grain to be tested is placed in the middle of the metal base (cast iron) germ side down and the metal base is then inserted into the end of the tube from the side of the tube (Plate 5-2). The steel bar hits the grain when the pin is taken out of the hole at the given drop-height.

The impact force on grain depends on the drop height of the standard 201.0g metal bar. In this experiment the drop height used for the HT-I drop tester was selected after preliminary experimentation (Appendix 8). The fixed drop height of the steel bar selected was 20 cm, the impact force was 0.392 J based on the following relationship (equation (5.1)):

$$\text{Impact Energy (J)} = mgh \quad \text{-----------------------} \quad (5.1)$$

where,

m = mass of impactor (0.2 kg),

g = acceleration due to gravity (9.8 m/sec) and,

h = drop height (0.2 m).

In practice, some of the impact (total) energy will be lost due to rebound, such that the absorbed impact energy (equation 5.2) becomes more relevant to the damage observed than total impact energy:

$$\text{Energy absorbed} = mg\,(h_1 - h_2) \quad \text{-----------------------} \quad (5.2)$$

where, h_1 is the original drop height, h_2 is the rebound height. However, it is assumed that h_2 is very small and negligible due to the large impact mass relative to the grain mass ($m_{bar} >>> m_{grain}$).

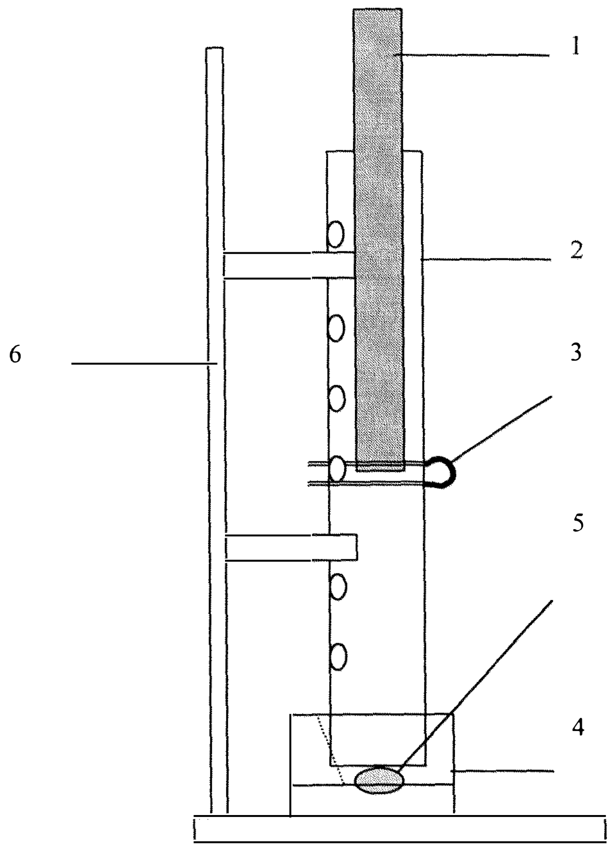


Figure 5-1. Diagram of HT-I drop tester and materials used. 1=Aluminium steel bar (201.0g) 2=Steel tube 3=Pin 4=Base 5=Maize grain 6=Stand.

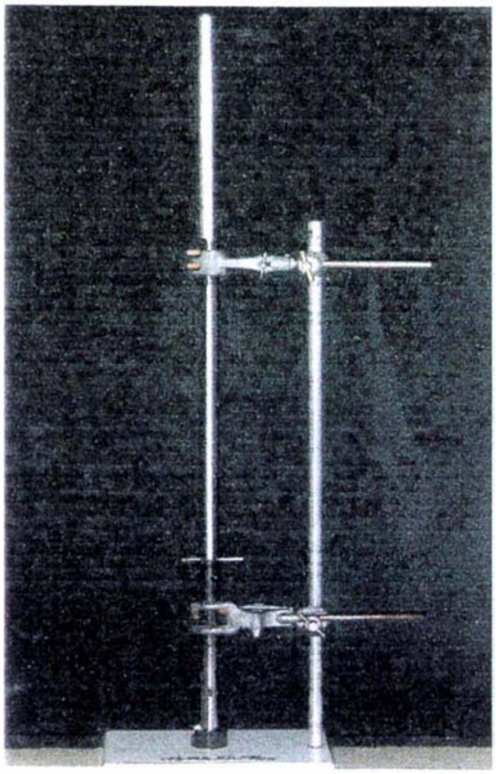


Plate 5-1. HT-I drop tester.

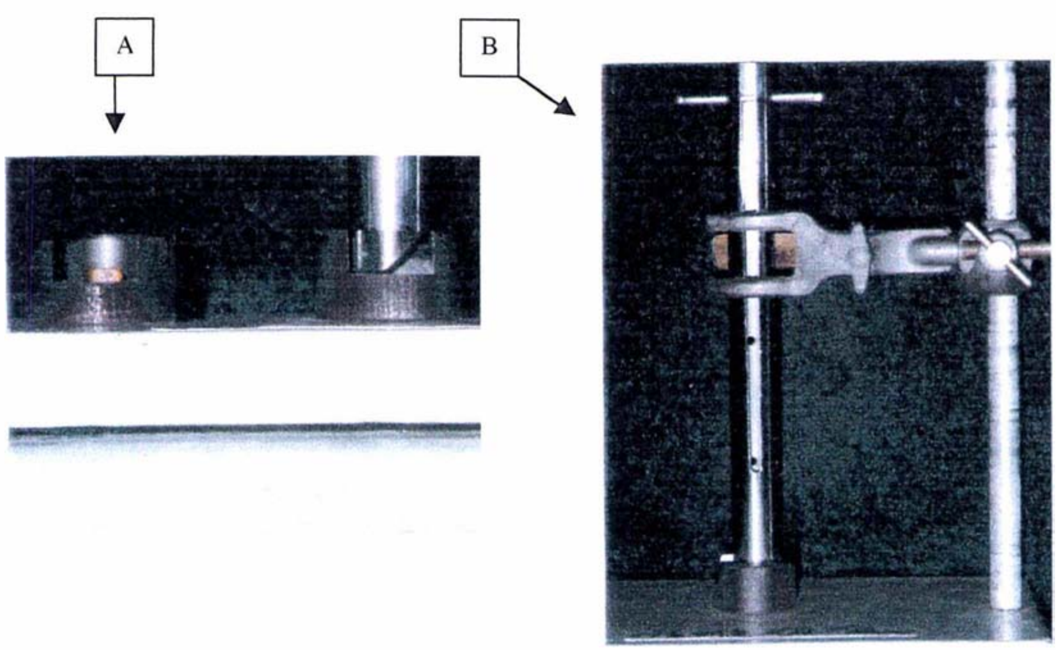


Plate 5-2. Positioning the base plate before breakage testing using the HT-I drop tester. The base plate is inserted at the end of the metal tube (A) and turned 90° so that the entire sample can be recovered after impact (B).

5-2-2. Maize hybrids and physical characteristics of maize grain

Medium flat grains for the two maize hybrids, Clint (H/S ratio; 3.3 (hard)) and P3902 (H/S ratio; 1.9 (soft)) were used in this experiment. The preparation for this material and comparison of the physical characteristics between the two hybrids were already described (Chapter 4, section 4-2-1. B and Table 4-3). Medium flat grains only were selected to remove variation due to grain size/shape (Martin et al., 1987; Montross et al., 1999). The aim of this grading was to ensure, as far as possible, that the breakage test results were attributable to hybrid and grain temperature effects only and not biased by grain size/shape differences.

5-2-3. Experimental procedures for the grain breakage test

A. The breakage test at various grain temperatures

Individual grains were dried from their harvest moisture content to a target moisture content of 13% at each of five drying temperatures (40, 60, 80, 100 and 120°C). For each hybrid, five grains were dried at each temperature, but this was replicated four times (total 20 grains per replicate). Each grain was positioned germ side down on the metal base plate of the HT-I drop tester before being placed in the oven (Plate 5-2). When the grains reached the target moisture content of 13%, 5 grains were removed from the oven and tested individually, immediately.

At the same time a reference sample of 20 grains in a single layer was placed into the oven for periodical weighing until the weight calculated to be that at the target moisture content of 13% was reached.

Grain temperature was measured using a temperature probe and Squirrel data logger (Plate 5-3 and Plate 5-4). A small hole was made from the crown or tip to the centre of the grain with a hand drill and the temperature probe was inserted (Plate 5-3). Another two probes were used to measure the oven and ambient air temperatures (Plate 5-5).

As a control, another 20 grains from each hybrid were dried at 20°C in a controlled temperature room (20±1°C, 65% RH) until the target moisture content was reached.

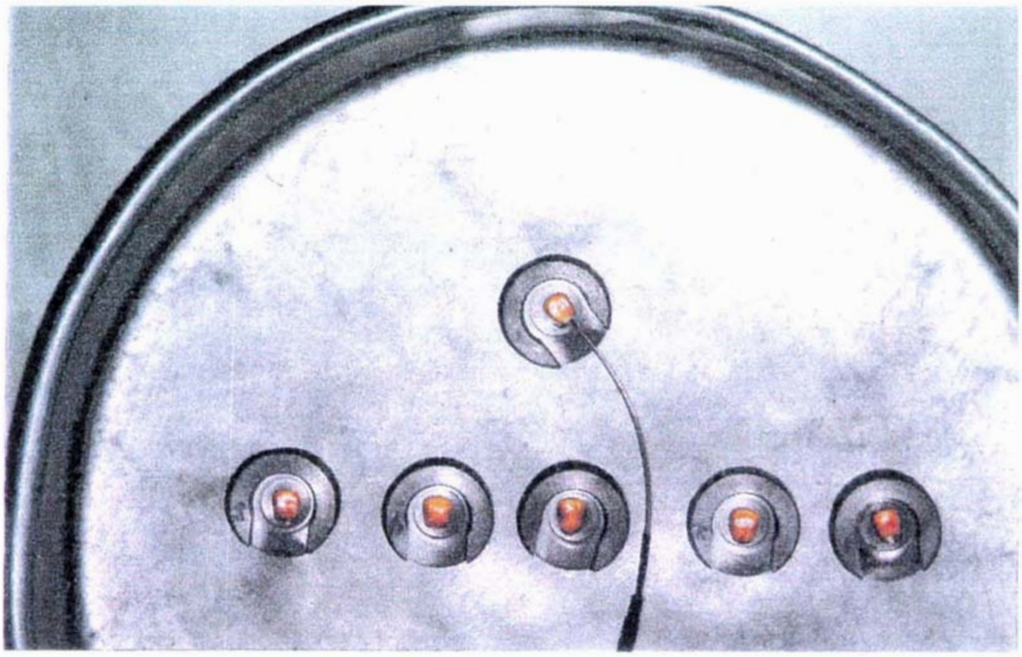


Plate 5-3. Positioning the five maize grains on the base plates before drying. An extra grain was used for measuring grain temperature during drying and cooling.

Plate 5-4. Squirrel data logger for measuring grain, oven, and ambient temperature during testing.

Plate 5-5. Oven, HT-I drop tester and data logger for measuring grain breakage and temperature; oven, and ambient temperature were also measured during testing.

B. Breakage at various times after drying

Three replicates were tested at 0, 2, 4, 6, 8, 10, 20, and 30 minutes after drying. A prepared sample of 40 grains per test were arrayed on a small tray and put into each of two ovens (60 and 120°C) until the grains were at the target moisture content (13%). After drying, 40 grains were removed from the oven and placed at ambient temperature. From the dried sample, five grains were selected and tested immediately (0 minutes) after drying, a further 5 grains were tested at 2 minutes after drying, a further 5 grains were tested at 4 minutes after drying and this was sequentially repeated at 6, 8, 10, 20 and 30 minutes after drying at ambient temperature (approximately 20°C, 65-70%RH). This was repeated four times for one replicate. During drying and cooling, the temperature of the grain was monitored using an extra grain (Plate 5-3).

C. Grain shrinkage and breakage after drying at six temperatures

To measure grain shrinkage after drying at various drying temperatures, another 20 grains from the same sample per replicate (three replicates per treatment) were numbered from 1 to 20 on the grain surface using an indelible pen and the dimensions of each grain measured using calipers before drying. The drying air temperatures used were 20, 40, 60, 80, 100, and 120°C, and grains were dried from their initial moisture content to the 13% target grain moisture content. After drying, grains were cooled at ambient temperature for 72 hours. The dimensions of the numbered grains were then re-measured. These same samples were then tested for breakage.

5-2-4. Data analysis and modeling

A factorial arrangement of treatments in a completely randomized design was used to evaluate the effect of hybrid and grain temperature on breakage susceptibility. Data were analyzed by analysis of variance using the general linear models procedure (PROC GLM) of SAS (SAS, 1985). Significant interactions between independent variables were presented by plotting the data means on bar-graphs and calculating LSD values appropriate for testing at a significance level of $P < 0.05$.

The data for the percentage breakage as a function of grain temperature at the time of testing were fitted to an exponential model (equation (5.3)) and the coefficients of A_{bk} and b from the fitted models were subsequently analyzed by ANOVA:

$$\text{Breakage (\%)} = A_{bk}e^{-b \bullet GT} \qquad \text{--} (5.3)$$

where, A_{bk} = maximum grain breakage, b = rate, and GT = grain temperature at the time of testing (°C).

The data for the percentage breakage of maize grain at various times after drying were fitted to a Mitscherlich function (equation (5.4)) (Seber and Wild, 1989) and the coefficients of A_t, b, and c from the fitted models were analyzed by ANOVA:

$$\text{Breakage (\%)} = A_t(1\text{-}e^{-b(t + c)}) \qquad \text{-------------------------------------} (5.4)$$

where, A_t = asymptote, b = rate, c = initial grain breakage, and t = time after drying at ambient temperature (minute).

5-3. Results

5-3-1. Changes of grain temperature during drying and cooling

Figure 5-2 shows changes in grain temperature of the two maize hybrids during drying at 120 ± 2°C and cooling at ambient temperature (20 ± 1°C, 65-70% RH). Grain temperature was initially around ambient temperature just before drying and increased rapidly as the maize grain was exposed to the drying air temperature. The maximum grain temperature was normally below drying air temperature and was maintained until the end of drying (arrows). After removing from the oven, grain temperature decreased sharply and it reached ambient temperature within 10 minutes. The pattern of grain temperature change was similar between the two hybrids. However, the grain temperature of P3902 (soft) increased more rapidly than that of Clint (hard).

Table 5-1 shows grain temperatures at the time of breakage testing of the two maize hybrids dried at various drying air temperatures. It took about 10 minutes for P3902 to reach a grain temperature of around 100°C and 20 minutes for Clint. The maximum grain temperature of the two hybrids during drying was about 110°C when maize grain was dried at 120°C.

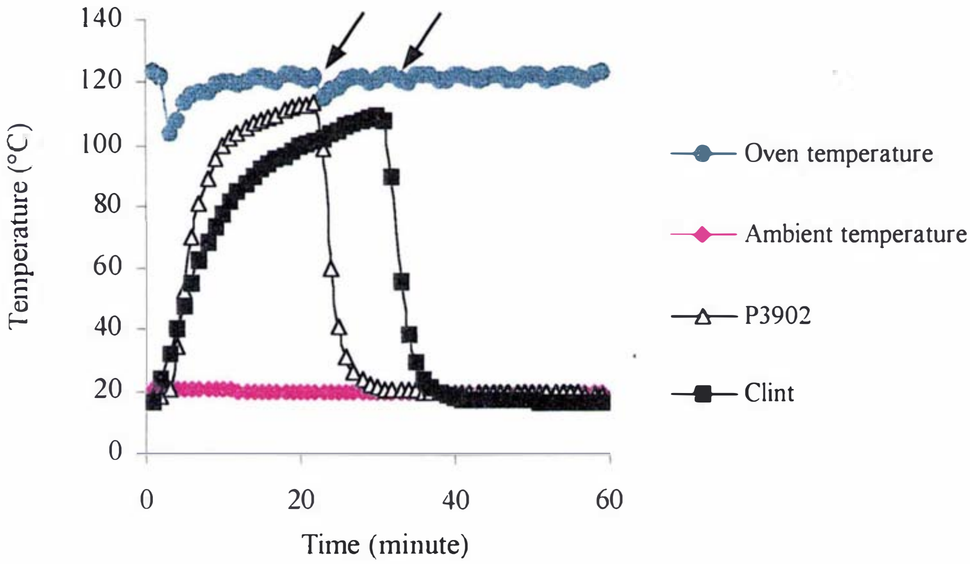


Figure 5-2. Changes in grain temperature of the two maize hybrids during drying (at 120°C) and cooling (ambient temperature; 20 ± 1°C, 65-70% RH).

Note: arrows indicate the time taken for the grain to reach the target grain moisture content of 13%.

The pattern of grain temperature change for the two hybrids during drying and cooling was similar at every drying air temperature. The maximum grain temperature was closer to drying air temperature as the temperature decreased (Table 5-1) this might be due to a longer period of exposure to the lower drying temperatures. For both hybrids, grain moisture content at the time of breakage testing was about 13.5% both before and after cooling (data not shown).

Table 5-1. Grain temperatures at the time of breakage testing of two maize hybrids dried at various drying air temperatures.

	GT (°C)		
DT [‡] (°C)	**P3902 (soft)**	**Clint (hard)**	**Average**
120	109.0	110.8	110
100	90.3	97.0	94
80	77.5	78.8	78
60	58.9	58.9	59
40	39.7	40.2	40
20	20.0	20.0	20

[‡] Note: DT = Drying air temperature, GT = Grain temperature at the time of breakage testing

5-3-2. Breakage of maize grain at various grain temperatures

Figure 5-3 shows the relationship between breakage susceptibility and grain temperature. The breakage of maize grain was very sensitive to the grain temperature at the time of testing. Both hybrids Clint and P3902 were plastic and had minimal breakage at high grain temperatures of from 78 to 110°C (also see Plate 5-6).

However decreasing grain temperature increased breakage exponentially. The hybrid P3902 (soft) had significantly higher percentage breakage than Clint (hard) when the grain temperature was lower than 40°C (Figure 5-3).

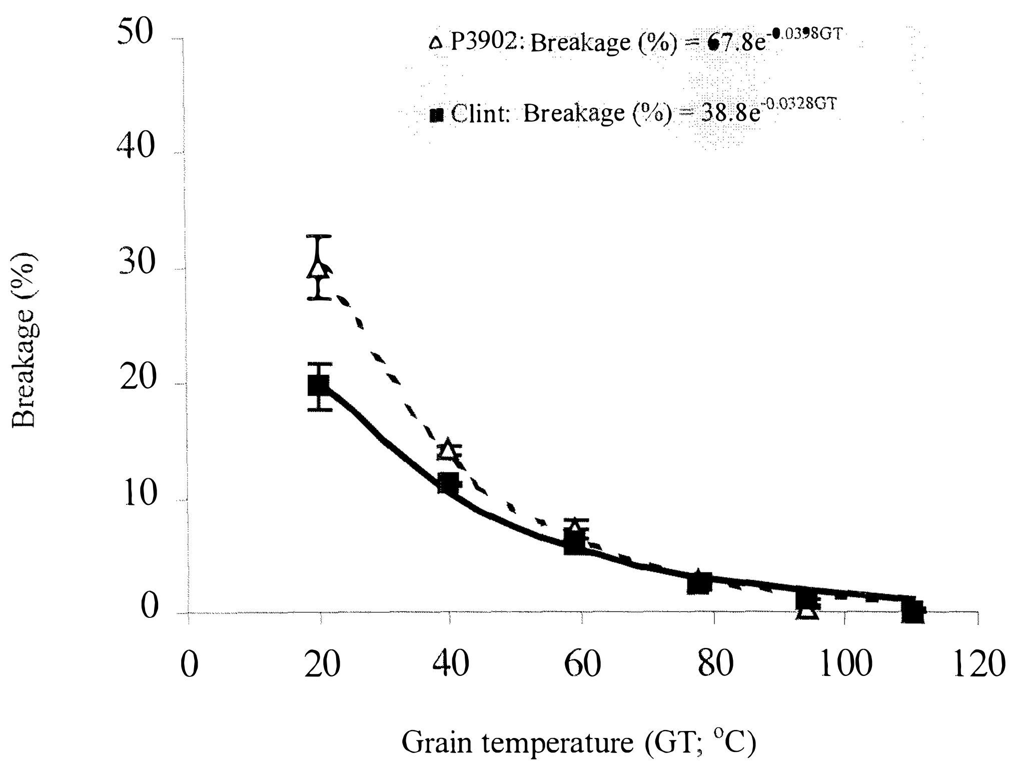


Figure 5-3. The relationship between breakage susceptibility and grain temperature.

Note: An exponential model (equation 5.3) was fitted to grain breakage at various grain temperatures:

Breakage (%) = $A_{bk}e^{-b\cdot GT}$

where, A_{bk} = maximum grain breakage, b = rate, and GT = grain temperature at the time of testing (°C).

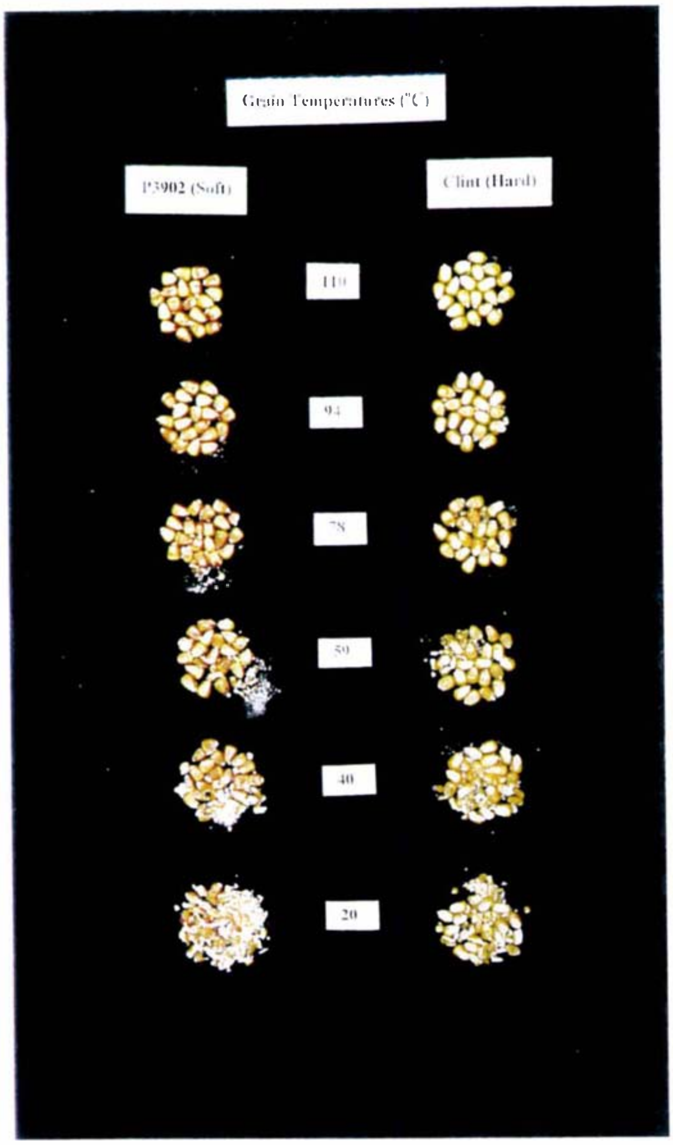


Plate 5-6. Grain breakage at various grain temperatures.

Table 5-2 presents the parameters for the exponential function (equation 5.3) for maize grain breakage at various grain temperatures at the time of testing. The hybrid P3902 (soft) had significantly higher predicted maximum breakage (A_{bk}) than the hybrid Clint (hard). While, the rate of increase in grain breakage with temperature for the two hybrids did not differ as grain temperature decreased from 110°C to 20°C.

Table 5-2. Comparison of the parameters A_{bk} (maximum) and b (rate) for breakage susceptibility of maize grain of two maize hybrids as a function of grain temperature (GT) at the time of testing.

		Parameters for exponential model for grain breakage ‡	
		A_{bk}	b
Hybrid (HYB)	P3902	67.8	0.0398
	Clint	38.8	0.0328
Significance		*	NS
LSD (5%, df_{err} = 4)		26.2	-

‡ Note: NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively.

Breakage (%) = $A_{bk}e^{-b \bullet GT}$

Where, where, A_{bk} = maximum grain breakage, b = rate, and GT = grain temperature at the time of testing (°C)

5-3-3. The effect of drying air temperature on grain breakage after cooling

Table 5-3 shows the comparison of the percentage breakage of two maize hybrids after drying at six temperatures and cooling at ambient temperature in a single layer for 72 hours. The average percentage breakage did not differ with hybrid, but did drying temperature and there was a significant interaction between hybrid and drying temperature for the percentage breakage.

Both hybrids had about 29% average breakage after drying. The percentage grain breakage was significantly higher at drying air temperatures of 60°C or higher. At 20 and 40°C, the average grain breakage for the two hybrids was about 25%. At drying temperatures between 60°C and 120°C, the average grain breakage for both hybrids was about 30 to 32% (Table 5-3).

Table 5-3. Comparison of the percentage breakage of two maize hybrids after drying at six temperatures and cooling at ambient temperature in a single layer for 72 hours.

		Breakage (%) ‡
Hybrid (HYB)	P3902	28.9
	Clint	29.2
Significance		NS
LSD (5%, df_{err}=24)		-
Drying temp. (DT)	20°C	24.8
	40°C	24.6
	60°C	30.3
	80°C	29.5
	100°C	32.6
	120°C	32.3
Significance		*
LSD (5%, df_{err}=24)		5.6
	Interactions	
HYB x DT		**

‡ Note: NS, *, **, or *** ; Non significant or significant *F* at <0.05, 0.01, 0.001, respectively.

Figure 5-4 shows the interaction between hybrid and drying temperature for percentage grain breakage after cooling at ambient temperature for 72 hours. The difference of percentage grain breakage between the two hybrids was not consistent as drying temperature increased from 20 to 120°C. For example, the hybrid P3902 had significantly (10%) greater breakage than the hybrid Clint at 20°C drying, but the hybrid Clint had significantly higher breakage at 100°C drying than the hybrid P3902. The percentage grain breakage between the two hybrids at the range of drying temperatures of 40 to 80°C and at 120°C did not differ significantly.

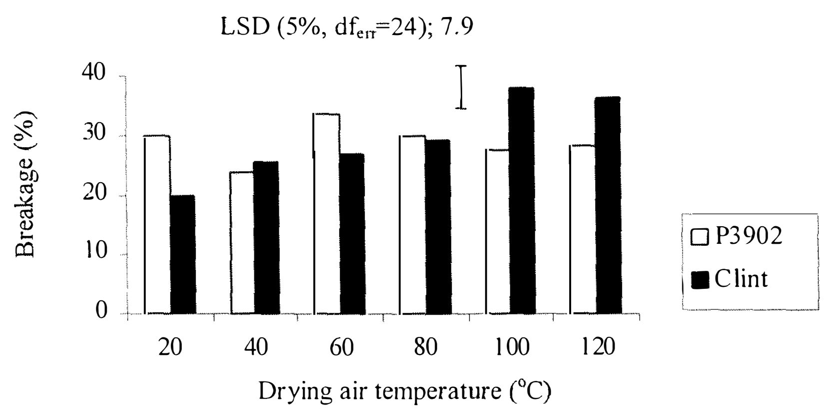


Figure 5-4. The interaction between hybrid and drying temperature for percentage grain breakage (after cooling at ambient temperature for 72 hours).

5-3-4. Breakage of maize grain at various times after drying

Figure 5-5 and Plate 5-7 shows the change in grain breakage (%) during cooling at ambient temperature in the two maize hybrids after drying at 60°C and 120°C. Percentage breakage of the two maize hybrids increased rapidly for the first ten minutes after drying at both 60°C and 120°C, and had reached the asymptotes after about ten minutes cooling at ambient temperature (20±1°C and 65-70% RH) in a single layer (Figure 5-5 and Plate 5-7).

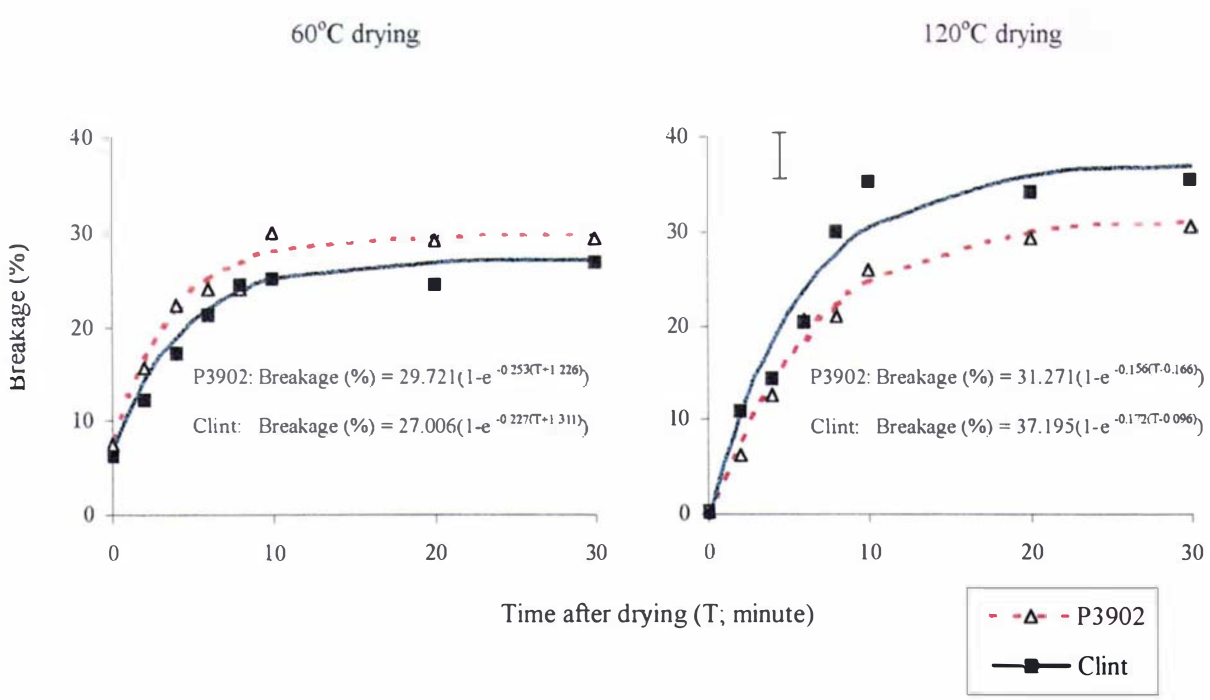


Figure 5-5. The change in maize grain breakage during cooling at ambient temperature (20±1°C and 65-70% RH) after drying at 60 and 120°C.

Note: The bar in the plot presents the LSD (5%, df_{err}=8) for the asymptote, A_t is 5.6.
The Mitscherlich function (equation 5.4) fitted to grain breakage times after drying was:
Breakage (%) = $A_t(1-e^{-b(t+c)})$

where, A_t = asymptote, b = rate, c = initial grain breakage, and t = time after drying at ambient temperature (minute).

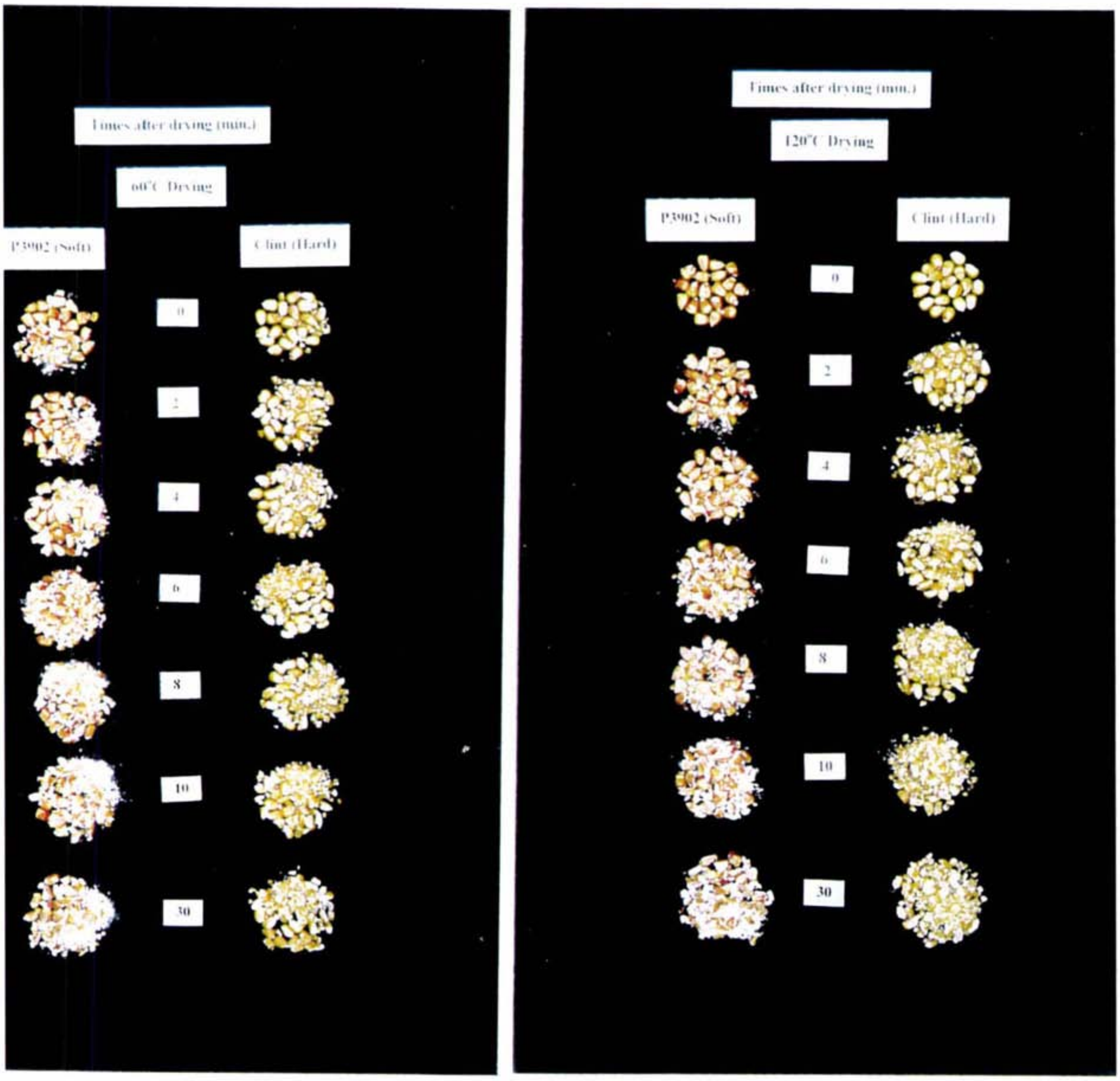


Plate 5-7. Grain breakage with time after drying at 60 and 120°C at ambient temperature (20±1°C; RH 65 to 70%) cooling.

The Mitscherlich function was fitted to the chronological development of percentage grain breakage after drying at 60 and 120°C, the parameters were compared to evaluate the rate and extent of grain breakage for the two hybrids, P3902 and Clint (Table 5-4 and Figure 5-5). The Mitscherlich model predicted the most observed real value of grain breakage about an average of 95%. In this model, A_t indicates an asymptote, which represents the predicted highest value of the percentage breakage, b indicates the rate increase in percentage breakage, and c provides the predicted initial grain breakage value for the two hybrids (Seber and Wild, 1989).

As seen in Table 5-4, A_t (asymptote), b (rate increase in breakage), and c (constant factor for initial percentage breakage) did not differ significantly between the two hybrids, indicating that the extent and rate of percentage breakage between the two hybrids did not differ significantly from 0 minutes to 30 minutes after drying. An average A_t,(asymptote) for the two hybrids was 30.5 and 32.1, for P3902 (soft) and Clint (hard), respectively.

Table 5-4. Comparison of the Mitscherlich function parameters for percentage breakage of maize grain during cooling at ambient temperature (20±1°C and 65-70% RH) after drying at 60 and 120°C.

		Parameters for exponential model for grain breakage ‡		
		A_t	b	c
Hybrid (HYB)	P3902	30.5	0.204	0.530
	Clint	32.1	0.200	0.608
Significance		NS	NS	NS
LSD (5%, df_{err} = 8)		-	-	-
Drying temp. (DT)	60°C	28.4	0.240	1.269
	120°C	34.2	0.164	-0.131
Significance		**	NS	**
LSD (5%, df_{err} = 8)		4.0	-	0.728
		Interactions		
HYB x DT		*	NS	NS

‡ Note: NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

The Mitscherlich function fitted to grain breakage times after drying was:

Breakage (%) = $A_t(1-e^{-b(t+c)})$

where, A_t = asymptote, b = rate, c = initial grain breakage, and t = time after drying at ambient temperature (minute).

Similarly, there was no significant difference for b between the two drying temperatures, indicating that the rate increase in grain breakage for the two hybrids did not significantly differ with drying temperature. On the other hand, A_t and c differed significantly between the two drying temperatures, indicating that the asymptote and initial percentage breakage for the two hybrids differed significantly with drying temperature. The average initial grain breakage for the two hybrids was about 7.5% at 60°C and minimal at 120°C drying (Figure 5-5). The average asymptotic breakage for the two hybrids was 28.4% at 60°C.

Interestingly, there was a significant interaction between hybrid and drying temperature for A_t (Table 5-4 and Figure 5-5). The hybrid P3902 (soft) had a similar A_t between the two drying temperatures, but for Clint the A_t increased significantly for the 120°C drying (Figure 5-5), indicating that the viscoelasticity of Clint changed more.

5-3-5. Shrinkage of maize grain after drying at six temperatures

Figure 5-6 presents percentage shrinkage of grain dimensions (length, width, and thickness) of the two maize hybrids after drying at six temperatures.

Grain dimension in Clint (hard) was reduced more than P3902 (soft) for all three parameters after drying at most drying temperatures. As the drying air temperature increased from 20°C to 120°C, grain dimension shrinkage (%) reduced significantly, but the shrinkage of length and width in both hybrids declined generally less than thickness.

The thickness shrinkage in P3902 (soft) decreased significantly more than that of length and width at high drying air temperatures (100 and 120°C) (Figure 5-6), indicating that high drying temperature increased the thickness of the soft hybrid, P3902 (puffed). On the other hand, reductions of grain dimension in Clint (hard) decreased to a lesser extent than P3902 as drying air temperature increased from 20°C to 120°C, and the dimension reduction pattern was similar for length, width and thickness (Figure 5-6).

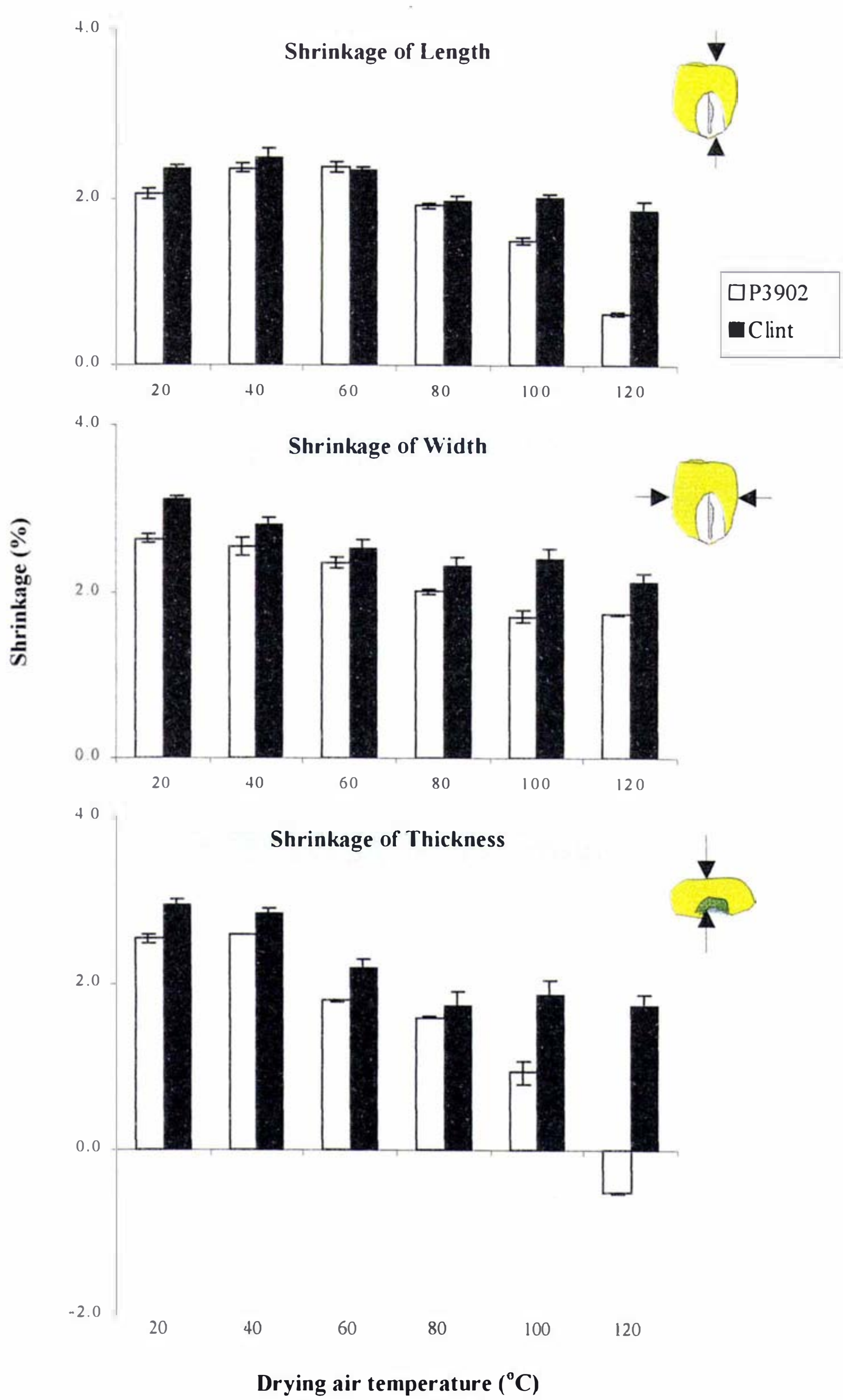


Figure 5-6. Comparison of the percentage shrinkage in grain dimension of two maize hybrids dried at various drying air-temperatures.

Table 5-5 summarizes differences in the shrinkage of length, width, and thickness between the two maize hybrids at each drying temperature.

There were significant linear and quadratic relationships between the differences in grain length and thickness shrinkage and drying temperature, indicating that grain length and thickness of Clint were reduced more than that of P3902 as drying temperature increased from 20 to 120°C.

However there was no significant linear and quadratic relationship between the differences of grain width shrinkage, indicating that the difference of grain width reduction between the two maize hybrids was similar along with drying temperatures from 20°C to 120°C.

Table 5-5. Difference in percentage shrinkage between Clint and P3902 at different drying air temperatures.

	Difference of dimension (%) ‡		
Drying Temp. (°C)	Length	Width	Thickness
20	0.33	0.47	0.40
40	0.13	0.27	0.27
60	-0.07	0.17	0.40
80	0.07	0.30	0.13
100	0.50	0.67	0.93
120	1.23	0.43	2.30
	Contrasts		
Linear	***	NS	***
Quadratic	***	NS	***

‡ Note: The difference of dimension = %Clint shrinkage - %P3902 shrinkage
NS, *, **, or *** ; Non significant or significant F at <0.05, 0.01, 0.001, respectively.

5-4. Discussion

The results of this experiment showed that breakage of maize grain was also very sensitive to the grain temperature at the time of testing and the difference in breakage was significant at a range of grain temperatures from 20°C to 110°C. Both the hard and soft endosperm maize hybrids had minimal breakage (%) at high grain temperatures such as 94 and 110°C (Figure 5-3 and Plate 5-6) even though grains had dried down to a moisture content (13%) that normally induces a high percentage breakage of maize grain (Herum and Blaisdell, 1981; Miller et al., 1981b).

The exponential model (equation 5.3) for grain breakage according to grain temperature at the time of testing successfully predicted the real value of grain breakage (Figure 5-3) and comparison of the model parameters clearly explained the extent and the rate increases in grain breakage at various grain temperatures (Table 5-2). For example; comparison of the exponential function parameters indicated that the two hybrids had similar rate increases in grain breakage as grain temperature decreased from about 110°C to 20°C, even though the two hybrids had different percentage grain breakage as grain temperature was lower than 40°C (Figure 5-3).

The grain temperature has been noted as a minor factor that affects grain breakage at the time of testing (Herum and Blaisdell, 1981). However, the result of this experiment and other published data (Miller et al., 1981b) suggested that grain breakage changed with grain temperature, particularly, at a range of between 20°C and 40°C, thus grain temperature also should be considered as a correction factor for an accurate measurement of grain breakage along with grain moisture content.

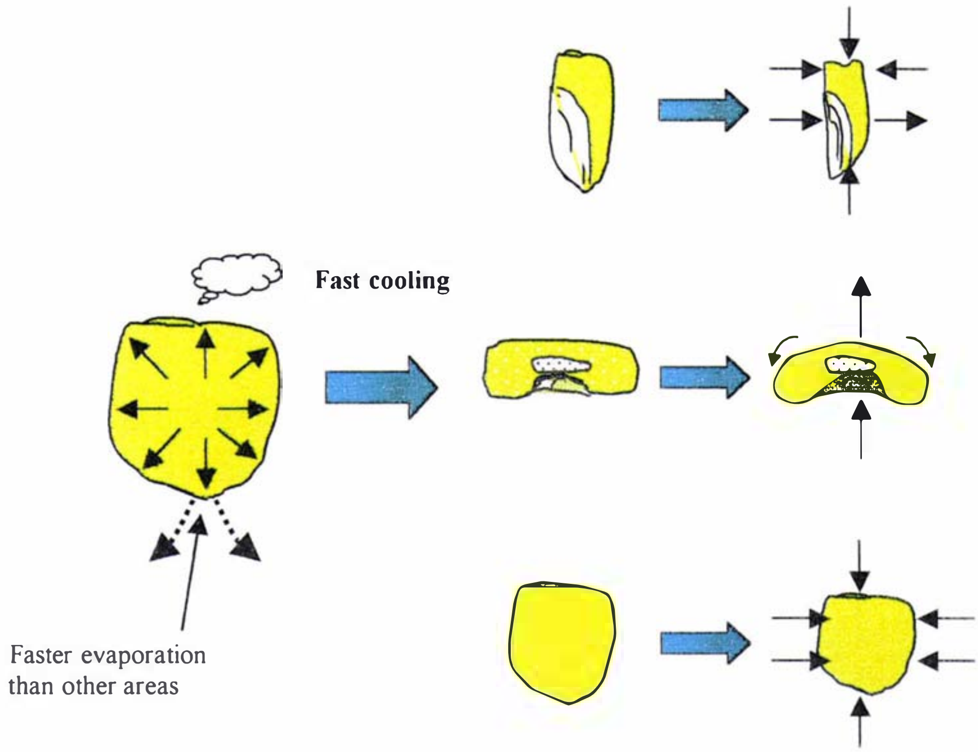
On the other hand, percentage breakage in P3902 and Clint increased rapidly after drying at 60 and 120°C during cooling at ambient temperature between 0 and about 10 minutes after drying as grain temperature decreased sharply (Figure 5-6 and Plate 5-7). The Mitscherlich model (equation 5.4) successfully predicted the real value of percentage grain breakage time after drying (Figure 5-5) and its parameters provided a more precise interpretation for the effect of hybrids and drying temperatures on the extent and the rate increases in grain breakage time after drying (Table 5-4).

Comparison of the Mitscherlich model parameters (Table 5-4) indicated there was a significant interaction between drying temperature and hybrid for the maximum value (A_t). As drying temperature increased from 60°C to 120°C, the predicted maximum value (A_t) of percentage breakage in Clint significantly increased (Figure 5-5), indicating that Clint had more heat sensitive endosperm characteristics than P3902.

From this result, an assumption for the mechanism of stress cracking development in maize grain could be suggested as followings:
Grains were more plastic at high grain temperatures (> 60°C) even when they were dried down to a relatively low grain moisture content (e.g., 13%). However grains were getting rigid and they might lose their plastic characteristics (viscoelasticity) shortly after drying during cooling (Kirleis and Stroshine, 1990) and thus stress cracking started to develop in grains during cooling some times after drying instead of during drying (See also Chapter 4 section 4-3-1. Figure 4-4).

Another important physical change that occurred during drying and cooling was grain dimension shrinkage. Figure 5-7 shows a schematic diagram for maize grain dimension shrinkage after high temperature drying and fast cooling. The reduction of grain dimension shrinkage due to high temperature drying and fast cooling is important evidence that could explain the reason why maize grain reduces in density after high temperature drying.

Kirleis and Stroshine (1990) reported that maize grain density decreased as drying temperature increased from 27°C to 93°C. They also found that a soft hybrid showed a greater decrease in density than intermediate and hard hybrids. Other researchers previously reported similar results after high temperature drying (Hall, 1972; Gunasekaran and Paulsen, 1985). However, there was little literature that had measured grain dimension shrinkage and density simultaneously with the same sample after high temperature drying. In this experiment grain density was not measured; however, the reduction of grain dimension shrinkage observed in the same sample before and after drying indirectly indicated that grain density must decrease as drying temperature increased from 20°C to 120°C (Figure 5-7).



❖ **High temperature drying (>60°C)**

- Increasing grain temperature
- Water vapor activate (fast evaporation)
- Plastic hard endosperm
- Decrease in grain weight (water loss)

❖ **Fast cooling**
(at ambient temperature)

- Shrinkage (Reducing thickness (L_c)) slightly bent to the opposite side to germ
- Decrease in grain density
- Stress cracking (Hardened hard endosperm)
- Increase in percentage breakage

Figure 5-7. A schematic diagram for maize grain dimension shrinkage phenomena after high temperature drying and fast cooling.

In addition, models developed in this study in relation with the percentage grain breakage and grain temperature at the time of testing might contribute to provide an important information for determining more accurate grain breakage in a single grain. The device developed (HT-I drop tester; Figure 5-1, Plate 5-1, and Appendix 7) in this study also must be useful to define stress cracking and grain breakage.

5-5. Conclusions

The hardening in hard endosperm due to high temperature drying and fast cooling is the key process that induces changes in the physical properties of maize grain (i.e., viscoelasticity).

The exponential model for predicting grain breakage for the hard (Clint) and soft (P3902) hybrids at six grain temperatures at the time of testing indicated that the two hybrids had minimal breakage at high grain temperatures (from 78 to 110°C), while decreasing grain temperature increased breakage exponentially. The predicted values also indicated that P3902 (soft) had a significantly higher breakage than Clint (hard) as the grain temperature fell below 40°C.

Comparison of the Mitscherlich function parameters for percentage grain breakage during cooling at ambient temperature after drying at 60 and 120°C indicated although there was no significant difference in the rate grain breakage developed between Clint and P3902, the predicted maximum value (A_t) of percentage breakage in Clint significantly increased as drying temperature increased from 60°C to 120°C, indicating that Clint had more heat sensitive endosperm characteristics than P3902. This result also supports the mechanism of development in stress cracking in maize grain.

Chapter 6 General discussion and conclusions

6-1. Factors affecting stress cracking in maize grain

6-1-1. Agronomic factors

One of the objectives of this study was to investigate several agronomic factors including hybrid, nitrogen and harvest moisture, which may affect stress cracking in maize grain. It has been noted that a hybrid that has a fast drying rate (in the dryer) has a high percentage stress cracking, especially when grains are dried at high drying-air temperatures (> 60°C) combined with high initial grain moistures (i.e., harvest moisture > 30%) (Thompson and Foster, 1963; Peplinski et al., 1975; Weller et al., 1990). Also, hard hybrids are more sensitive to stress cracking than soft hybrids (Kirleis and Stroshine, 1990). The results of this study generally agreed with previous reports. However, stress cracking in maize grains might not be necessarily be affected by drying rate and initial grain moisture and grain hardness, for example:

1) The hybrid Hmv565-3xE1386 (hard), had a significantly slower grain drying rate (Table 4-2), but the percentage checking in this hybrid did not significantly differ from that of the intermediate hybrid (CF06) over 72 hours after drying (Table 4-4),
2) The soft grain hybrid, Furio, had the lowest harvest grain moisture (Table 4-2), but it had the highest checking and SCI. Another soft hybrid, CF05 had a high harvest moisture (Table 4-2), but it had the lowest checking and SCI among the four hybrids (Table 4-4), and
3) Rounded grains had a lower H/S ratio than flat grains (Table 4-2), but rounded grains had a slower drying rate (within a size category) and a higher percentage of checking (Table 4-4).

This controversy might be due to heterogeneous chemical and physical structure in maize grain. In this study, P3902 was generally less susceptible to stress cracking than the other selected hybrids (Table 3-6 and Table 4-7). It has a dark yellow colour in its hard endosperm and looks less translucent than the other hybrids selected in this study. Thus it is suspected that endosperm characteristics related to colour and translucency in maize grain may affect the susceptibility to stress cracking.

On the other hand, grain size, shape, and hardness factors were found to be correlated with the MMF model (equation 4.4) parameters, which were developed for predicting stress cracking development in maize time after drying, indicating that: 1) the rounder the grain shape (i.e., greater the SDP), the higher the percentage of stress cracking in maize grain, and 2) the smaller the grain size (i.e., weight and length), the faster the development of stress cracking after high temperature drying (Figure 4-4 and 4-8).

Particulary, small round grains (within a hybrid) had a significantly higher percentage checking than large flat grains in soft and intermediate hybrids (Table 4-4 and Figure 4-3). Structural variation or non-uniform distribution in hard and soft endosperm in small grains (soft) might contribute to the marginal variation in grain drying rate (Table 4-9), and thus result in a higher susceptibility to stress cracking (Figure 4-4).

In practice, therefore, the morphological characteristics of maize grain should be considered as a factor for hybrid selection for the maize milling industries, because increased maize grain uniformity would reduce pronounced stress cracking, and thus improve end use quality. For example, from the results of this study (Figure 4-3), removing small and rounded grains would reduce checked stress cracking by up to 40 to 50% in some hybrids (CF05 and CF06) under the same drying conditions. This information is important, particularly, to grain handlers and processors who use raw material of maize grain for producing various industrial products for human consumption including grits, starch and masa.

Although it was found that a high grain moisture content at harvest increases stress cracking and breakage (Weller et al., 1990), in this study the effect of nitrogen (Table 3-6) and harvest grain moisture content on stress cracking in maize grain was small (Table 3-6 and Figure 3-13 and 3-14). This might be due to the predominant effect of post-drying cooling condition (i.e., cooling rate) on stress cracking (Figure 3-14).

Therefore, grain producers and dryer operators, who deal with maize for a raw material for a specific grain industry such as dry milling, should consider: 1) the proper application of nitrogen according to maize hybrid in terms of grain hardness, and 2) tempering or slow cooling for reducing stress cracking in grain at high temperature drying irrespective of grain harvest moisture and nitrogen.

6-1-2. Postharvest drying factors

The effects of drying air temperature on maize quality, especially stress cracking and breakage susceptibility have been the subject of extensive studies (Thompson and Foster, 1963; Gunasekran et al., 1985; Sarwar et al., 1989; Kirleis and Stroshine, 1990; Peplinski et al., 1994; see also Chapter 2 section 2-5-2). Thompson and Foster (1963) firstly noted that high-temperature (60-115°C) drying induced stress cracking in maize grain, and those grains were two to three times more susceptible to breakage than the same grains dried with unheated air. Many studies have supported this and most researchers concluded that increasing breakage susceptibility was associated with stress cracking mainly due to high drying air temperatures (White and Ross, 1972; Sarwar et al., 1989; Kirleis and Stroshine, 1990).

The results of this study, however, indicated that a high drying rate (i.e., fast moisture removal from the grain; more than 5% moisture removal per hour) or a high drying temperature does not necessarily create high percentage stress cracking. For example;

1) At the lowest cooling rate of 0.23 (°C/°C/min.)•10^{-2} (45°C-slow cooling (tempering)), grains had minimal checking and less than 15% multiple stress cracking and thus the SCI was less than 100 regardless of the level of drying air temperature between 50°C and 80°C (Figure 3-13 and 14) and;

2) Tempering following high temperature drying (>60°C) significantly reduced stress cracking (Table 4-10 and Figure 4-7).

Generally, few stress-cracked grains were found immediately after high temperature drying. Most stress cracking in maize grain developed chronologically up to 72 hours after finishing drying (Appendix 5 and Figure 4-4). Immediately after high temperature drying (100 and 120°C), grains were pliable, but grains are soon rigid shortly after drying (within about ten minutes) during cooling at ambient temperature (Figure 5-4 and Plate 5-7). This indicated that grain breakage and stress cracking is temperature dependent and controllable.

Figure 6-1 presents a possible mechanism of stress cracking in maize grain after drying at high temperatures (> 60°C). When grain is exposed to a high drying-air temperature such as higher than 60°C, internal stress (i.e., increasing temperature and moisture gradient) increases. During this stage the grain is soft and plastic (temperature dependent). This occurs until the grain temperature nears that of the drying temperature (Figure 5-2).

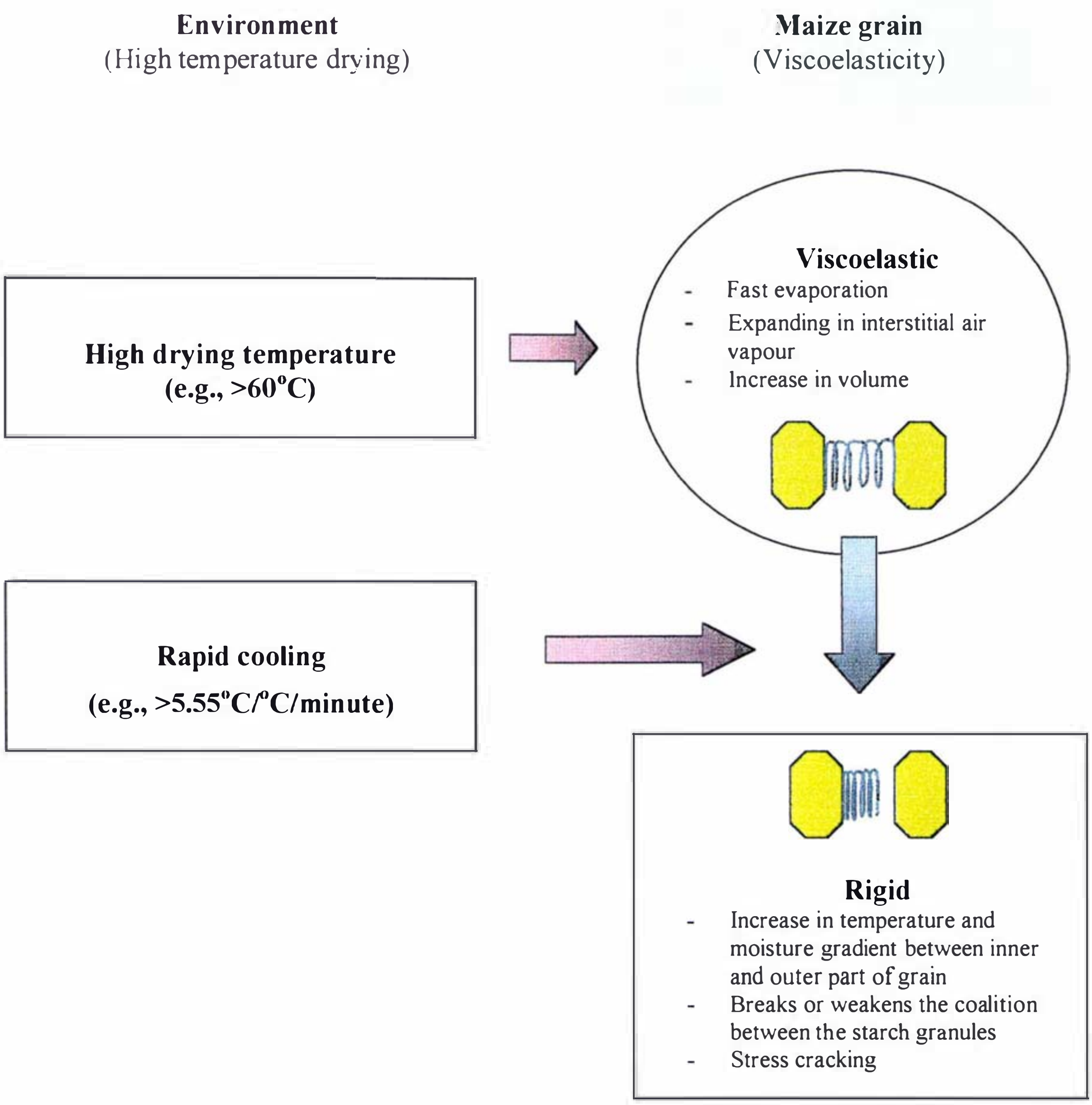


Figure 6-1. A possible mechanism of stress cracking in maize grain after high temperature drying.

As grain cools down quickly to a relatively low temperature after high temperature drying, it becomes rigid (Figure 5-4). Therefore, stress cracking developed not during or immediately after finishing drying, but some time after drying when grains were hardened and had cooled down to ambient temperature (Figure 4-4 and 4-6).

In contrast, low temperature drying such as ambient temperature (20°C) drying, did not cause much change in grain pliability during and after drying (Figure 5-2). Grains dried at such low drying temperatures have higher densities than those dried at high temperatures (Kirleis and Stroshine, 1990) and also no stress cracking (Figure 6-1).

However, stress cracking in grains following high temperature (>60°C) drying could be prevented by tempering or slow cooling (Brooker et al., 1992). Tempering following high temperature drying could maintain the plastic characteristics of maize grain and therefore stress cracking can be reduced significantly (Table 4-10 and Figure 4-7). In this study, it was found that the higher the drying-air temperature (e.g., 120°C), the higher the tempering temperature required to reduce stress cracking. Figure 6-2 summaries this beneficial effect of tempering temperature on stress cracking and breakage susceptibility in maize grain.

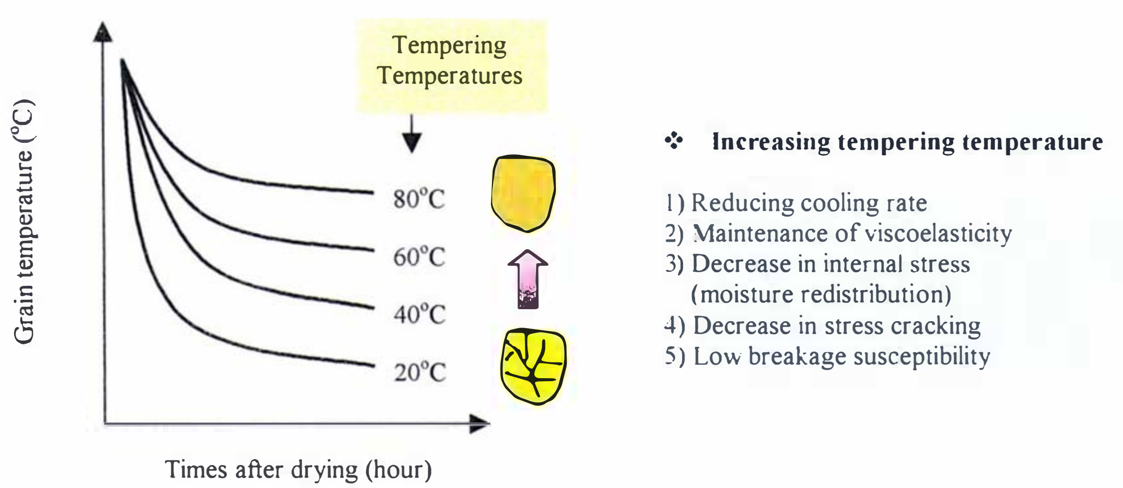


Figure 6-2. The effect of tempering temperature on stress cracking and breakage susceptibility in maize grain.

Therefore, when maize grain is dried at high temperature (conventional high temperature drying), tempering or slow cooling is necessary for reducing stress cracking to maintain high end-use quality.

6-2. Prediction models for stress cracking and grain breakage

In this study, several models were developed for predicting stress cracking and breakage susceptibility in maize grain time after drying. These models were successfully predict the real observed value and were useful to understand viscoelastic characteristics in maize grain, which was exposed to extreme drying and cooling stress (i.e., high temperature drying and rapid cooling).

The MMF model (equation 4.4) parameters explained the development of stress cracking in grain of different size, shape and hardness and also provided important information how and when stress cracking developed in grains. Particularly, the MMF model parameters were correlated with grain size, shape, and hardness factors and this made a possible generalizations for the effect of size and shape on stress cracking in grain of different size and shape (Table 4-6 and Figure 4-8). However, this generalization could not be extended to the hardness related factors because of the exception in hybrid, P3902. This implied that several unknown chemical attributes of maize grain (hard endosperm part) could be involved in stress cracking sensitivity.

Based on the relationship between percentage grain breakage and grain temperature, the exponential model (equation 5.3) was developed. This model provided a clearer explanation about the rate developing in percentage breakage for the soft and hard hybrids at a range of grain temperatures from 20 to 110°C (Table 5-2). On the basis of this model, it is suggested that grain temperature at the time of testing should be considered as an adjusting factor for determining a more accurate grain breakage susceptibility.

The Mitscherlich function (equation 5.4) for the changes in grain breakage time after drying for the two hybrids also successfully predicted the observed grain breakage and provided valuable information how the grain viscoelasticity changed along with decreasing grain temperatures. This model supported the chronological development in stress cracking in maize grain.

The models and the breakage tester (HT-I drop tester) developed in this study will be useful for grain industries. For example, The MMF model can be applied for predicting the levels of stress cracking in maize grains during postharvest drying and cooling. If physical characteristics of grain are noted such as shortest diffusion pathway (SDP), hardness ratio, and drying rate, then it is possible to predict the rate and the extent of stress cracking in grains at a given drying temperature and cooling rate.

The single grain breakage device, HT-I drop tester, has several benefits compared to conventional breakage testers such as Stein Breakage tester (SBT) and Wisconsin breakage tester (WBT): 1) it can be used to define a more accurate grain breakage for single grains at a given grain temperature and moisture content; 2) it is a simple; and 3) inexpensive tool for grain growers and dryer operators.

6-3. Final conclusions

In this study several crop management and grain drying factors affecting stress cracking and breakage susceptibility in maize grain were investigated. For reducing in stress cracking in grains, slow cooling was the most effective. However, several other factors also significantly affected the susceptibility to stress cracking and breakage in maize. With respect of the size and shape characteristics, small and round grains were more sensitive to stress cracking. In practice, removing these grains could be reduce stress cracking by up to about 40 to 50% and improve maize end use quality, particularly, when selecting a soft or intermediate hard hybrid. Several models developed in this study successfully predicted the real observation and were very useful for understanding the grain viscoelastic characteristics. These models provided valuable information about the behavior of grain under extreme drying and cooling stress. The analyses of parameters of these models indicate that the hardening in hard endosperm due to high temperature drying and fast cooling is the key process that induces stress cracking in grain times after drying. Therefore, tempering or slow cooling, which can retain the viscoelasticity of the artificially dried maize grain, is necessary for the reduction of stress cracking and high end-use quality of maize.

6-4. Recommendations for future studies

1) Physical attributes for the maize post-drying period: A future study of grain breakage at various grain moisture contents and high grain temperature would be needed to provide a useful piece of information that indicates when and how maize grain is hardened during high temperature drying (i.e., the limitations for viscoelasticity of maize such as grain temperature and grain moisture content). This would also provide information how to deal with maize grain after high temperature drying.

2) The effects of drying temperatures on chemical changes in maize: The severity of stress cracking may also indirectly indicate heat induced chemical damage in maize such as starch gelnatinization and protein denaturation. Low-temperature drying usually has little effect on maize quality, while, high drying-air temperatures can decrease protein solubility, protein moisture-binding capacity, and enzyme activity (Peplinski et al., 1994). Unfortunately, the chemical properties (i.e., changes in albumins and prolamins) of maize grain was not measured in this study. It is suspected that tempering following high temperature drying may affect maize chemical properties (i.e., starch gelatinization and protein denaturation). If this happens, how does it happen, what would be changed, and thus how is the maize quality affected? The answers to these questions should be provided from future studies.

3) Measurement of stress cracking: There are modern and automated methods for detecting stress cracking in maize grain such as by using low-power X-ray, machine vision techniques, and magnetic resonance imaging (MRI) (Gunasekaran, 1985; Watson, 1987a; Kim, 1991; Song and Litchfield, 1994, see also Chapter 2 section 2-5-2, F). In this study, however, stress cracking in maize grain was inspected visually. This visual methodology for measuring stress cracking is subjective (Miller et al., 1981b) and also time consuming. In future studies, it is expected that by using the methods mentioned above stress cracking in maize grain could be determined and observed more precisely. For example, it is possible to record the chronological development of stress cracking in maize grain by machine vision (i.e., video recording).

4) Other factors that affect stress cracking: There is little information about the effect of grain size/shape and hardness ratio on moisture re-adsorption rate and stress cracking in normal dent maize grain, which is the majority of raw material used for the food

industry (Eckhoff, 1992a). Another study is required to provide information as to how to deal with and process the different sizes/shapes of maize grains for producing high quality end-use products and also improve the efficiency of processing for each specific industry. For example, if flat and rounded maize grains have a different rate of moisture re-adsorption, removing either flat or rounded grains during reconditioning may improve uniformity and thus will be helpful for more efficient starch production in the wet milling processing.

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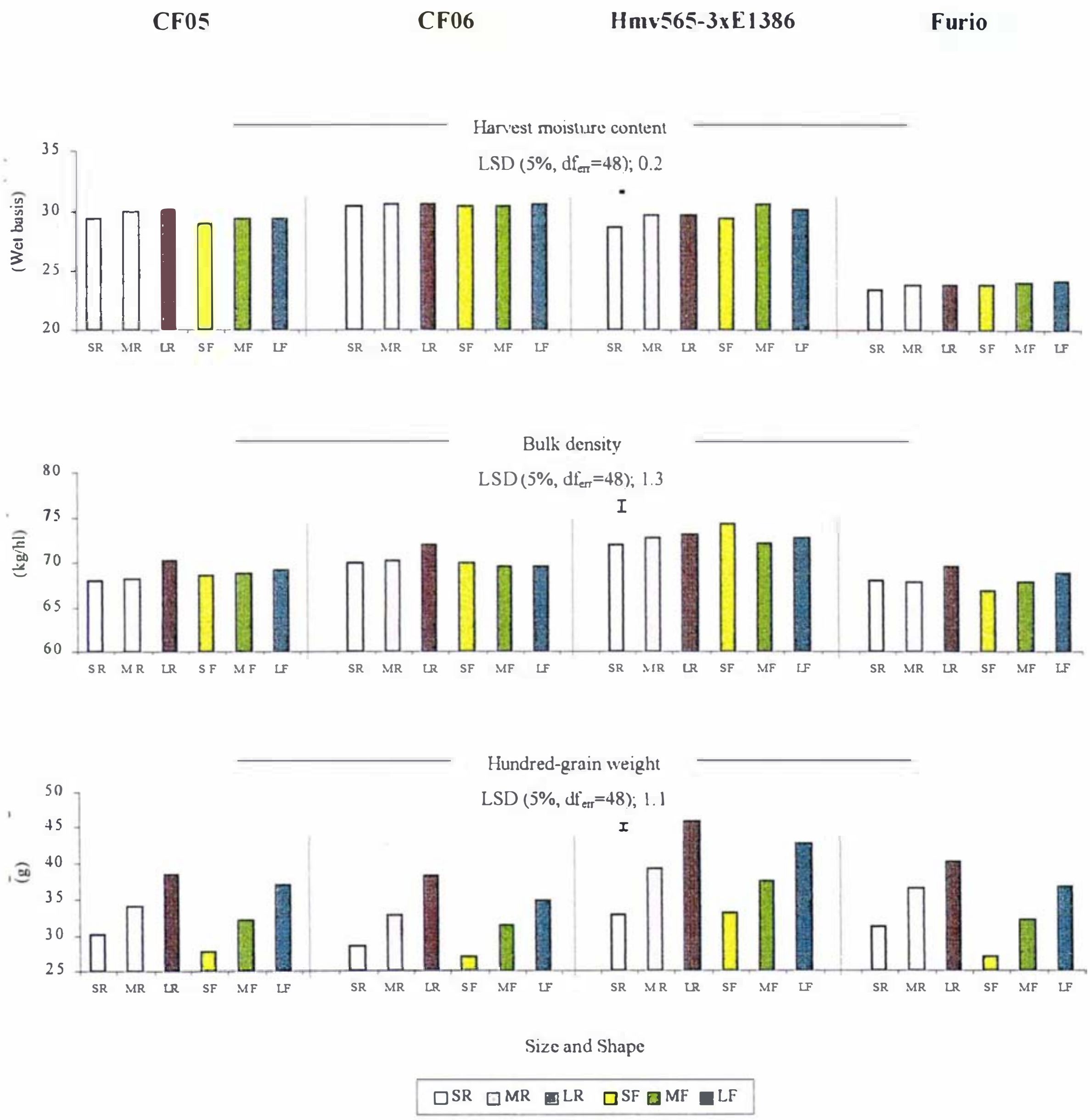
Appendix 1. Harvesting time and harvest moisture content (wet weight basis) of maize grain in the 1995-96 cropping season.

			Targeted Harvest Grain Moisture			
			30%		22%	
Hybrid	**Nitrogen**	**Block**	**DAS**	**HMC (%)**	**DAS**	**HMC (%)**
Furio	0kg N/ha	1	197	29.1	271	21.0
		2	204	30.3	269	21.0
		3	200	30.1	264	21.6
	230kg N/ha	1	200	30.4	270	21.0
		2	204	29.1	266	21.2
		3	197	29.0	264	21.2
P3753	0kg N/ha	1	186	29.8	253	22.3
		2	186	29.1	251	23.1
		3	186	31.0	248	23.6
	230kg N/ha	1	183	30.6	252	22.0
		2	183	31.7	249	23.1
		3	183	30.6	246	21.8
P3902	0kg N/ha	1	180	29.8	244	23.0
		2	181	30.3	241	22.9
		3	182	29.3	237	23.2
	230kg N/ha	1	178	29.8	242	22.8
		2	177	30.4	239	23.6
		3	179	30.7	235	23.7
Average			**188**	**30.1**	**252**	**22.3**

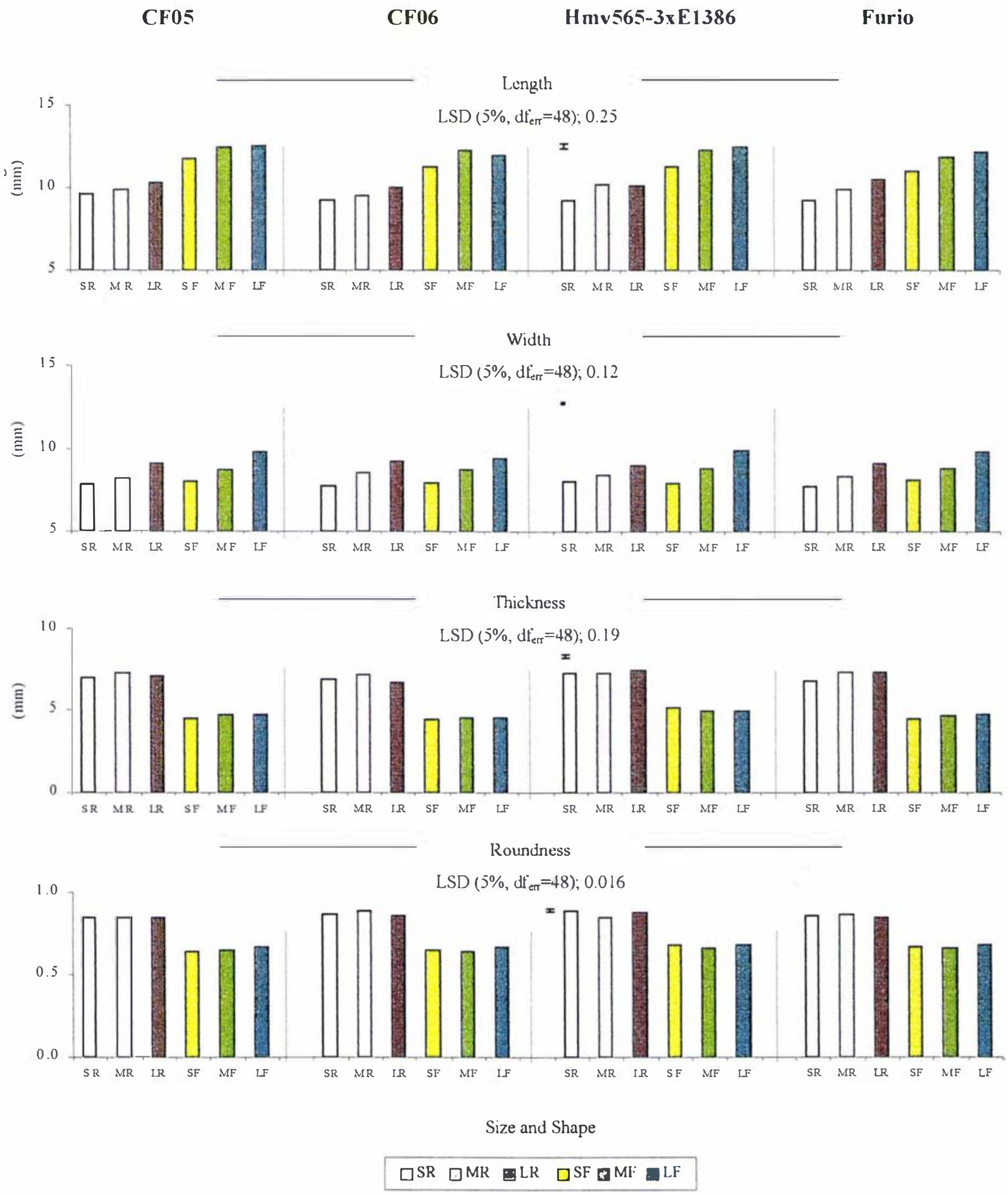
*DAS means days after sowing.
**HMC means harvest moisture content of maize grain (wet basis).

Appendix 2. Interactions of harvest moisture content, bulk density, and hundred-grain weight with grain size and shape and hybrid.



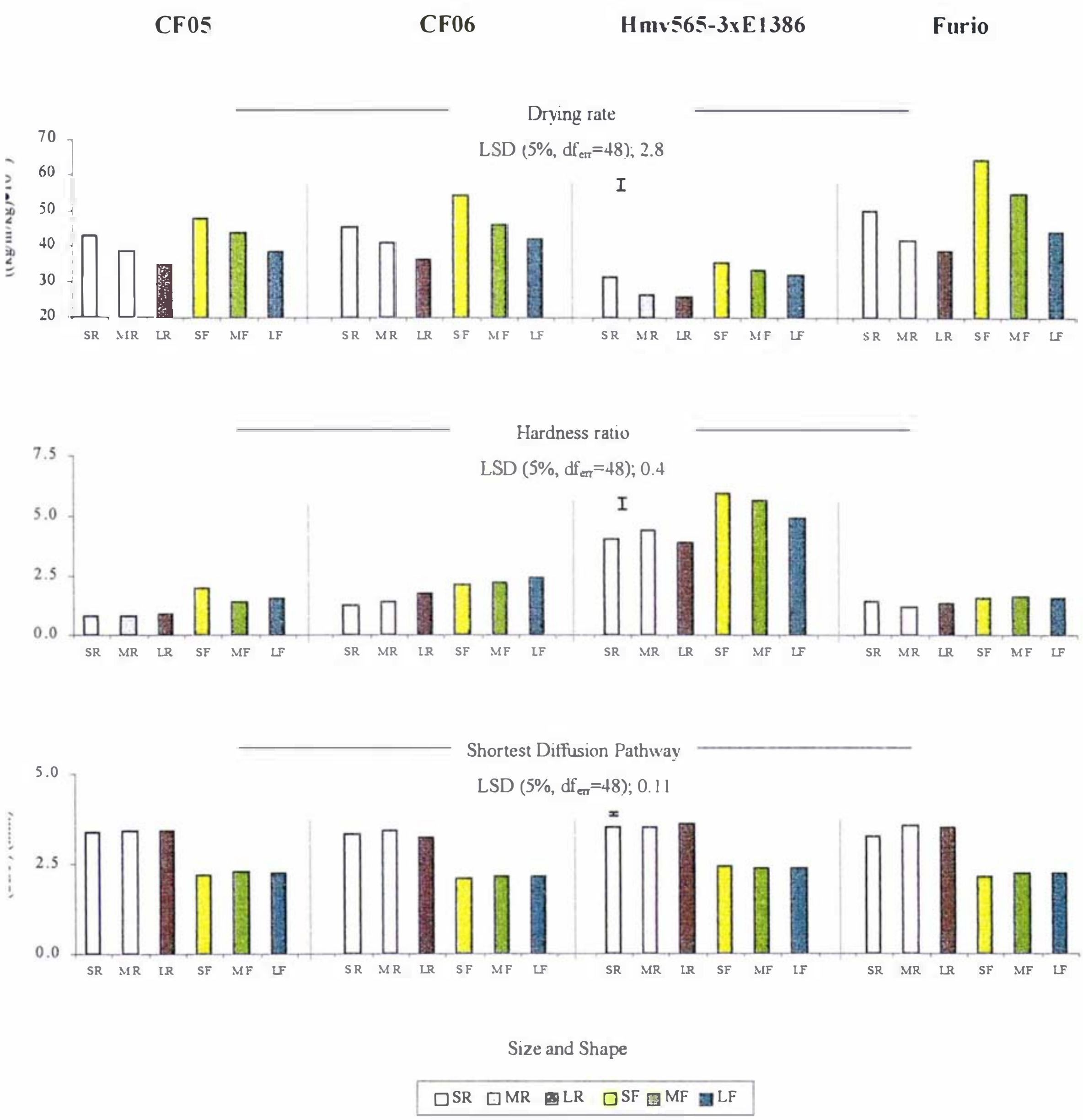
Note: SR = small round, MR = medium round, LR = large round, SF = small flat, MF = medium flat, LF = large flat.

Appendix 3. Interactions of grain dimension (length (L_a), width (L_b), and thickness (L_c)) and roundness (sphericity) with grain size and shape and hybrid.



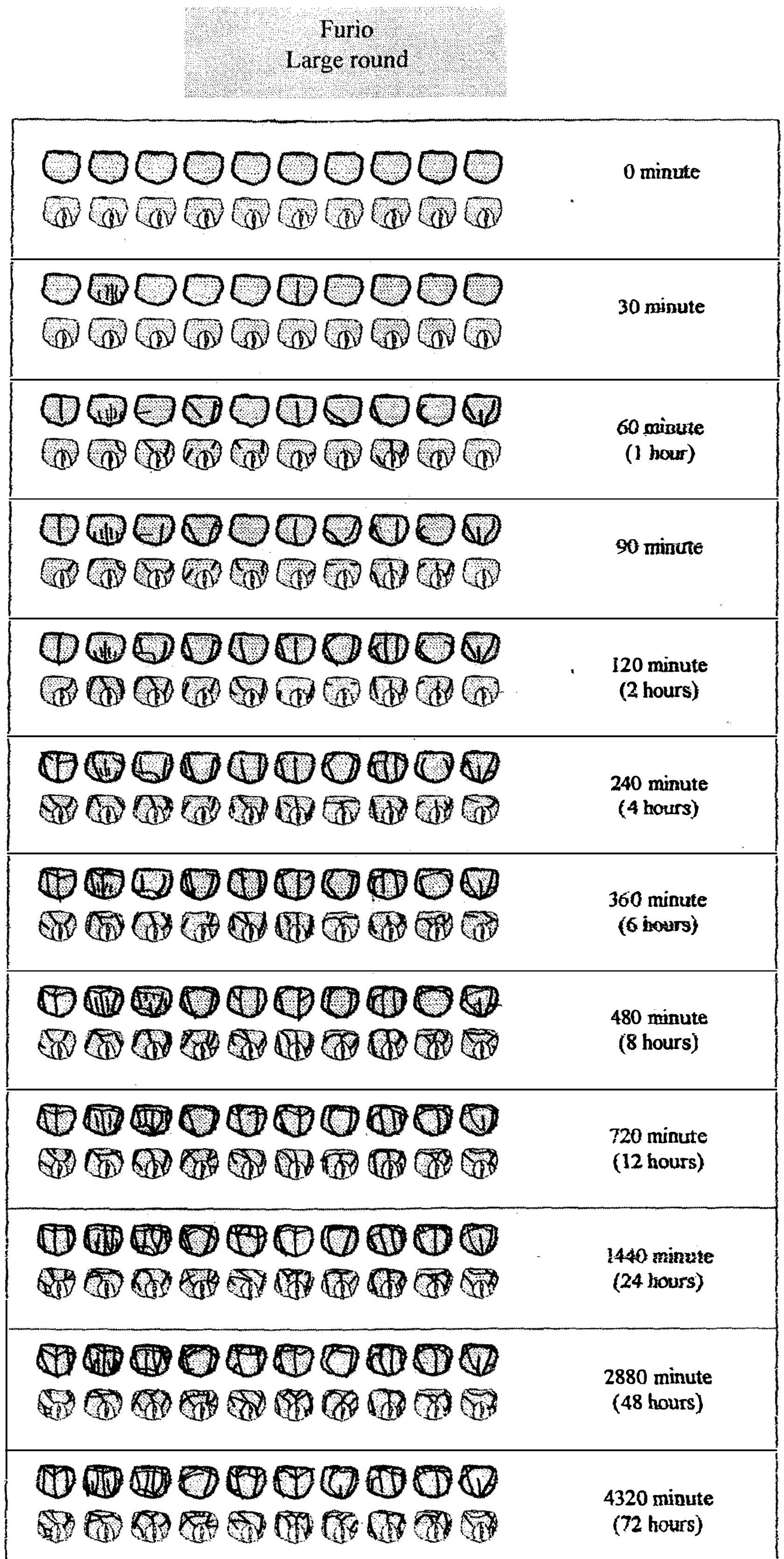
Note: SR = small round, MR = medium round, LR = large round, SF = small flat, MF = medium flat, LF = large flat.

Appendix 4. Interactions of drying rate, hardness ratio and shortest diffusion pathway (SDP) of maize grain with grain size and shape and hybrid.

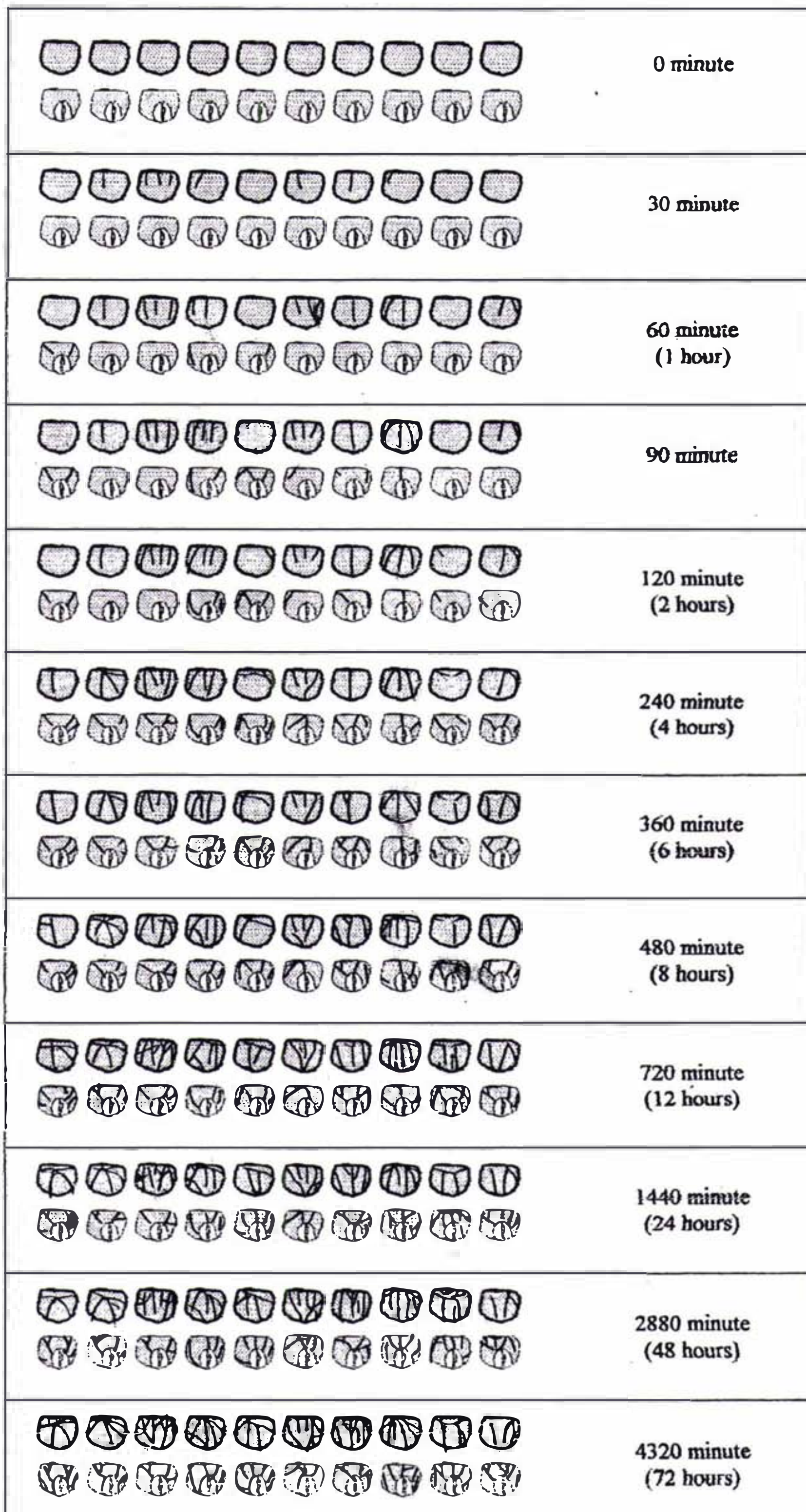


Note: SR = small round, MR = medium round, LR = large round, SF = small flat, MF = medium flat, LF = large flat.

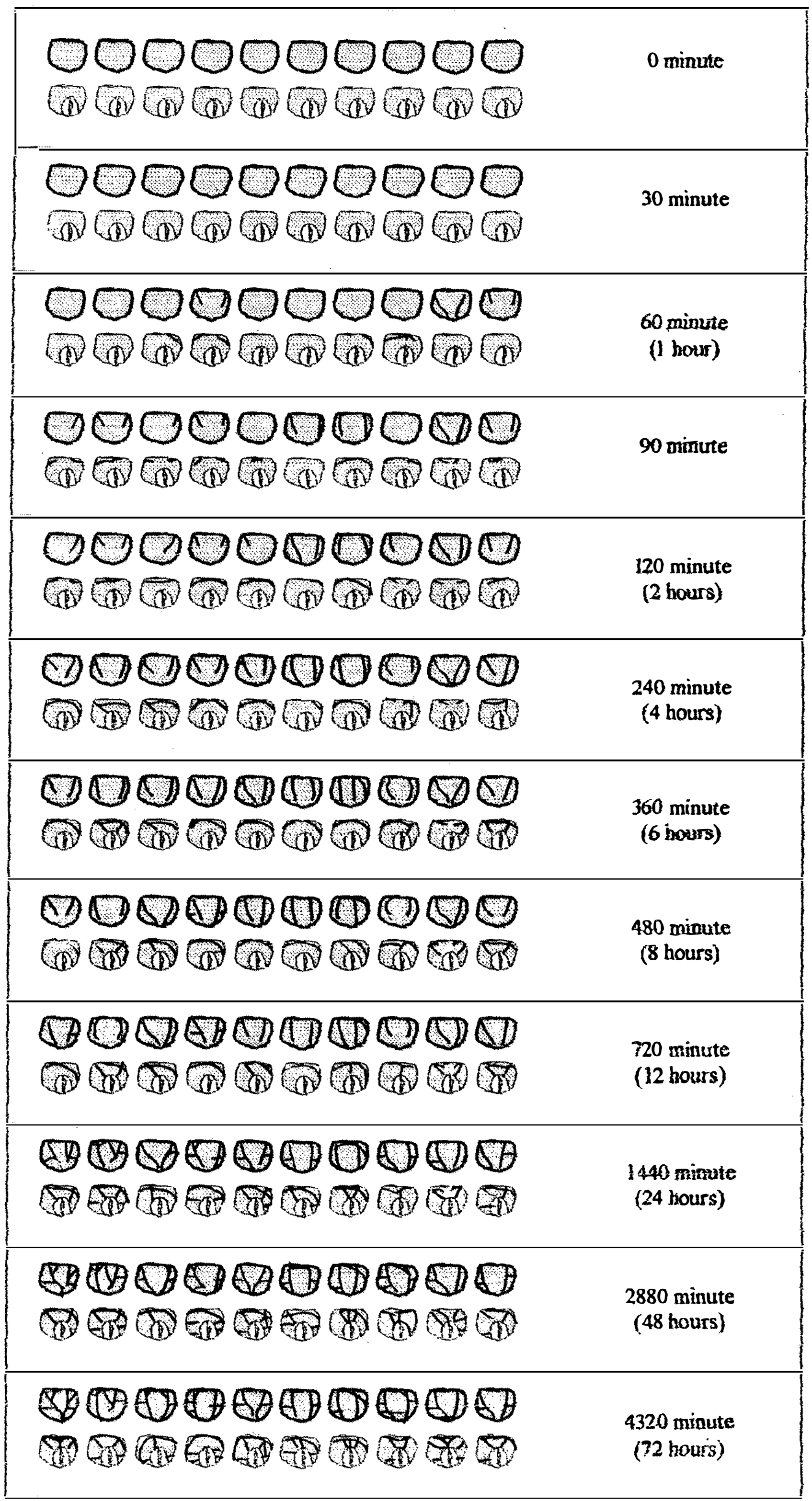
Appendix 5. Hand drawings of development of stress cracking in maize grains after drying at 60°C and cooling for 72 hours at ambient temperature.



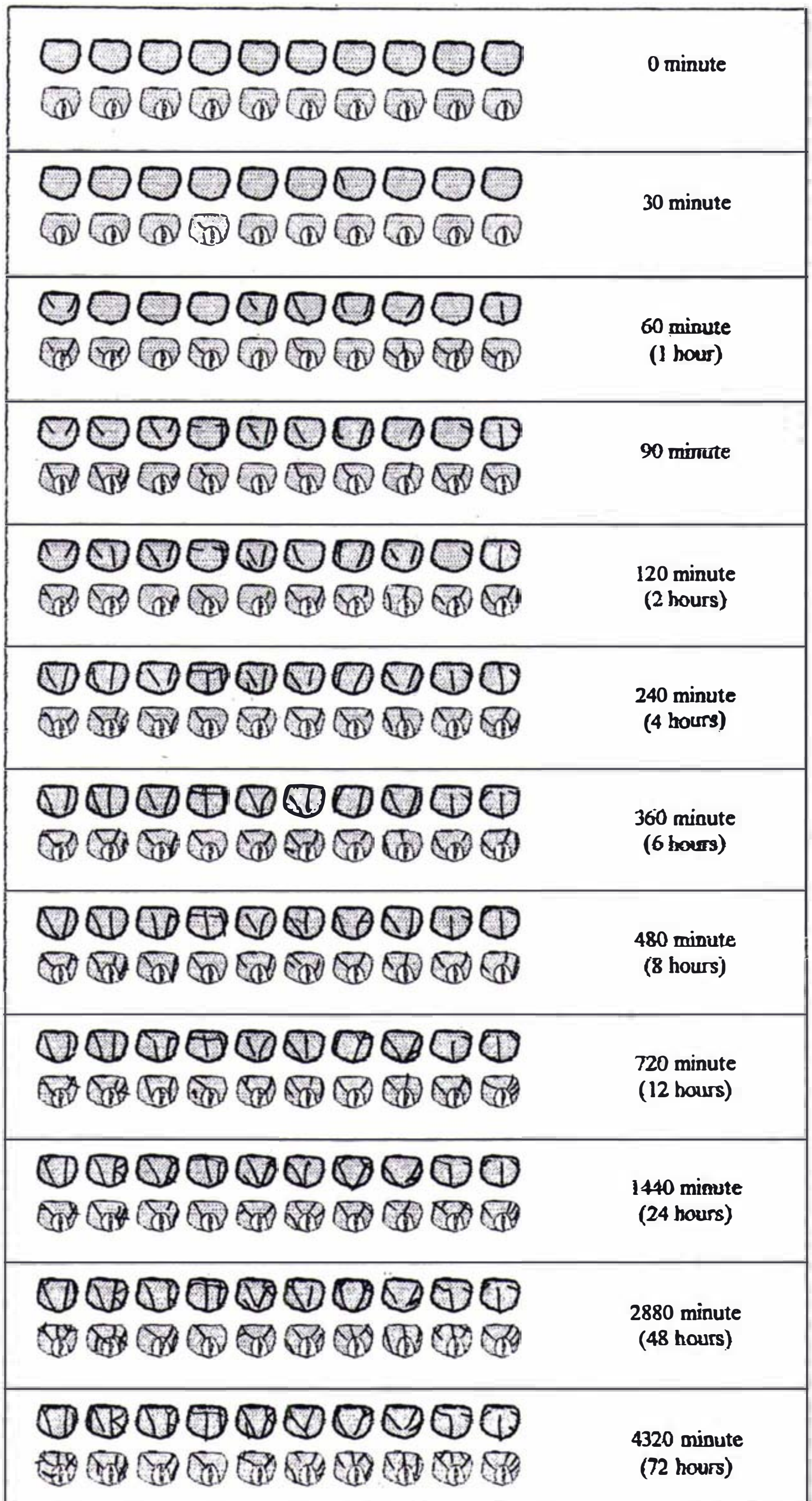
CF06
Small round



Hmv565-3xE1386
Large flat



CF05
Small flat



Appendix 6. The proportion of each category of grain as determined by the position on the maize cobs

❖ Procedure:

1. Two cobs per replicate were randomly selected (total of six cobs per hybrid).
2. Each maize cob was divided into quarters by length; the upper quarter = “top”; the base quarter = “bottom”; and the middle part was between the borders of the “top” and “bottom” of each cob.
3. Grains were hand shelled from each of the three positions, leaving 2 or 3 borderlines of grains around each “division”.

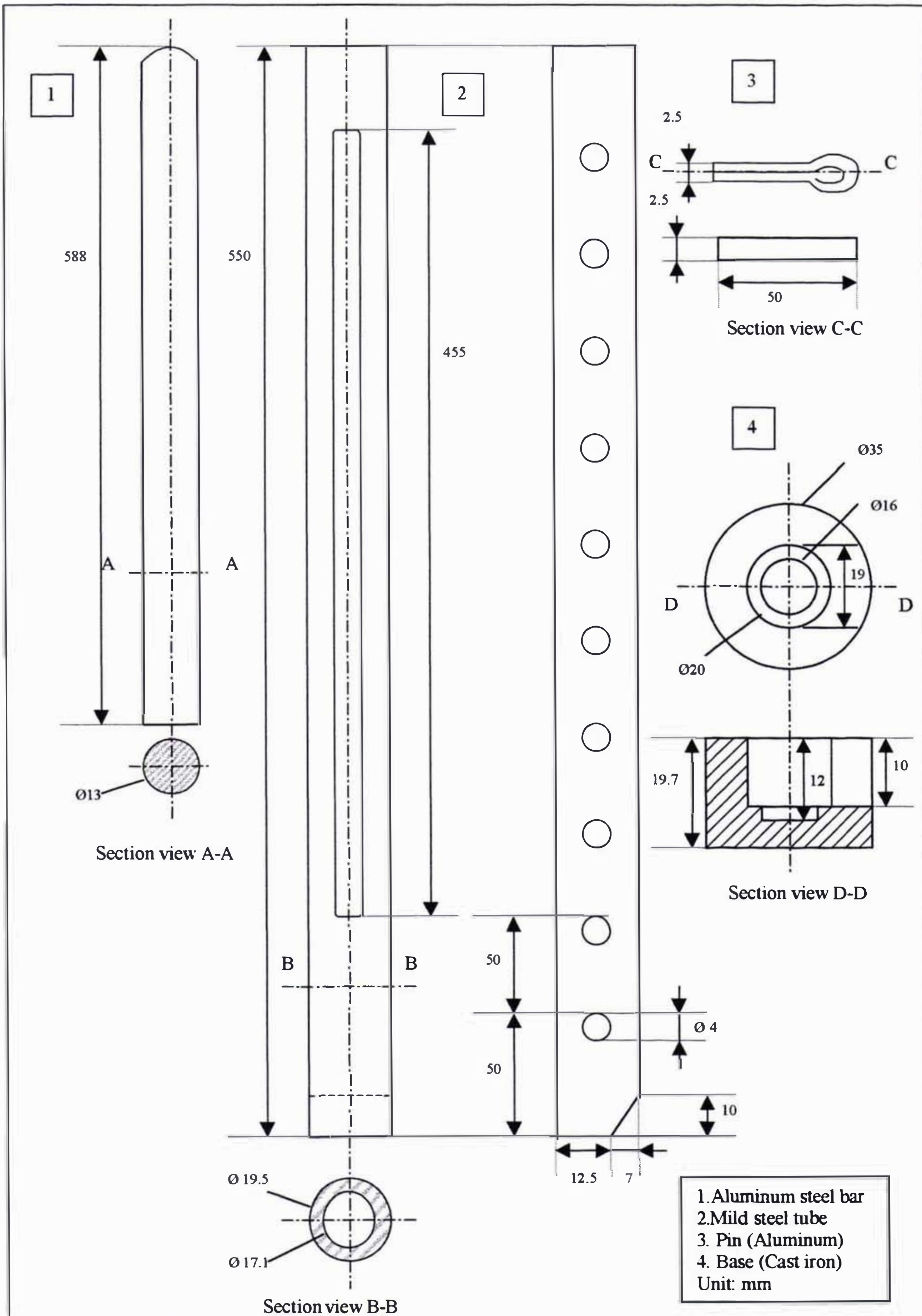
❖ Results:

The distribution (%) of various sizes and shapes in maize grains on the maize cob and their moisture content at harvest in 4 hybrids.

Hybrid	Position	SR	MR	LR	SF	MF	LF	MC
CF05	**Top**	3.1	0.0	0.0	11.4	0.6	0.0	27.0 (0.27)
	Middle	1.5	0.5	0.0	23.5	23.2	6.7	27.4 (0.73)
	Bottom	4.9	6.1	2.3	3.1	6.8	3.8	27.8 (1.77)
CF06	**Top**	3.4	0.2	0.0	13.6	0.9	0.0	29.1 (0.73)
	Middle	2.0	0.6	0.1	23.0	19.1	6.3	29.2 (0.92)
	Bottom	5.7	6.0	1.7	4.8	7.5	3.5	29.1 (0.32)
Hmv565-3 x E1386	**Top**	6.5	8.1	1.6	0.4	1.9	0.6	27.9 (0.91)
	Middle	0.6	4.0	5.6	0.5	7.8	31.1	29.8 (0.57)
	Bottom	0.2	3.3	15.9	0.0	0.5	11.5	29.6 (0.66)
Furio	**Top**	2.7	0.0	0.0	11.2	1.7	0.0	24.2 (0.48)
	Middle	1.9	0.8	0.1	13.0	31.5	8.2	24.5 (0.06)
	Bottom	2.6	4.7	3.4	1.5	6.5	8.6	24.5 (0.16)

‡ SR= small round, MR= medium round, LR= large round, SF= small flat, MF= medium flat, LF= large flat. SUM=sum of the percentage weight of maize grain at each position, MC=moisture content of maize at harvesting. Numbers in parenthesis are standard deviation.

Appendix 7. Detailed structure of each part of the HT-I drop tester.



Appendix 8. Pre-testing results and feasibility of using the HT-I drop tester.

1. Introduction

Breakage susceptibility is defined as the potential for maize grain fragmentation when subjected to impact force during handling or transport (AACC, 1983). Broken pieces, which pass a 4.76 mm (12/64 inch) round hole sieve, described by U.S. Grain Standards as broken corn and foreign material (BCFM) reduce both maize grade and value (Watson, 1987a). Various devices, including the Stein breakage tester (SBT), Wisconsin breakage tester (WBT), Missouri cracker, and USGML (U.S. Grain Marketing Laboratory) grain accelerator have been made and used for the measurement of breakage susceptibility of maize grain.

The standard measurement of breakage susceptibility (B.S.) using these devices is calculated as:

$$\%\ \mathbf{B.S.} = \frac{\textbf{(original weight – weight retained by 4.76mm round hole sieve)} \bullet \mathbf{100}}{\textbf{original weight}}$$

The factors that can affect breakage susceptibility are drying air temperature and grain hardness (Kirleis and Stroshine, 1990), drying rate (Gunasekaran and Paulsen, 1985), hybrids (Paulsen et al., 1983), cultural management in the field (Moes and Vyn, 1988), the grain moisture content at harvest (Weller et al., 1990), the grain moisture content at the time of testing (Herum and Blaisdell, 1981; Paulsen, 1983) grain size and shape (Martin et al., 1987), grain temperature (Herum and Blaisdell, 1981), and stress cracking (Gunasekaran and Muthukumarappan, 1993).

However, there has been limited study of grain temperature effects on breakage tests. Therefore, the HT-I drop tester[‡] was designed to test single grain breakage at high grain temperatures. The objective of this was:

To determine methodology for using the HT-I drop tester.

[‡] Acknowledgement: The development of the breakage device was assisted by Mr. Allan Hardacre (Crop & Food Research).

2. Material and Methods

The material used for the pre-test was ambient air dried grains of the maize hybrids, Hmv565-3xE1386 (hard) and Furio (soft). The grain moisture content was 11.3% (hard) and 11.9% (soft) (wet basis). The oven method was used for measuring grain moisture content (AACC, 1983). The sample grains used in this preliminary test were medium flat grains as described in Chapter 4. The simplified breakage testing procedure is presented in Figure 1. 20 grains per replicate were used in this experiment, so that the sample weight was approximately 7 to 8g. The drop height used was 5, 10, 15, 20, 25, 35 and 50 cm. The dropping aluminum metal weight was 201.0g. The energy used at each height was calculated using equation (1):

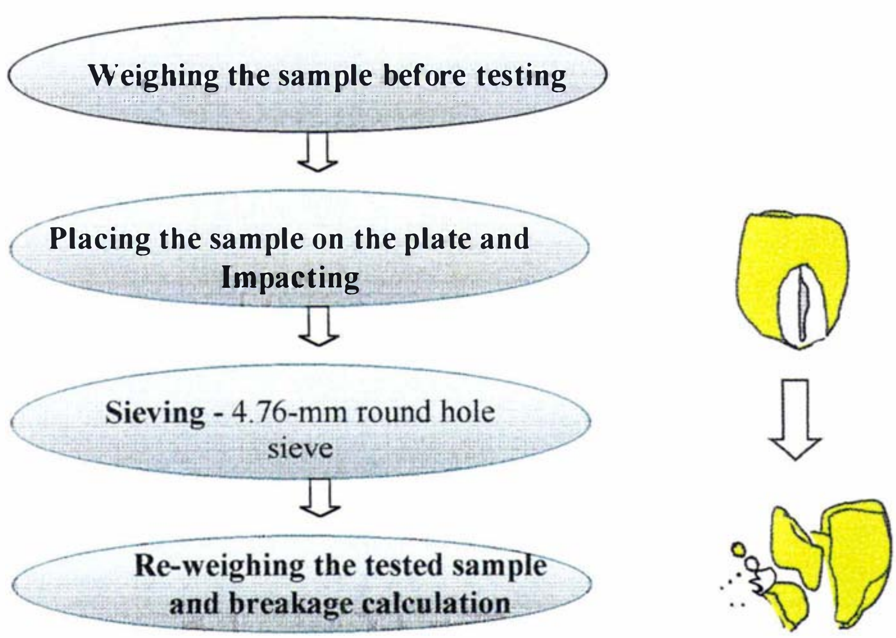
$$\text{Impact Energy (J)} = mgh \qquad (1)$$

where, m = weight of metal bar (201.0g $\approx$ 0.2kg),

g = gravity (9.8m/sec), and

h = drop height of metal bar (m).

Therefore the impact energy tested ranged from approximately 0.1J (5 cm) to 1J (50 cm).



$$\textbf{Breakage (\%)} = \frac{\textbf{(Original weight – weight retained by 4.76mm round hole sieve)} \bullet \textbf{100}}{\textbf{Original weight}}$$

Figure 1. Simplified procedure for the breakage test using the HT-I drop tester.

3. Results

The HT-I drop tester was used for determining maize grain breakage. Table 1 shows a comparison of the breakage (%) between the two hybrids. The percentage of fine particles of Hmv 565-3 x E1386 (hard) increased continuously from 5 to 50 cm of drop height. Furio (soft) had similar results, but it had a higher percentage of fine particles (Table 1).

The percentage breakage between the two hybrids differed from 10 cm to 35cm of drop height (Table 1). The impact at the drop heights over 35 cm (about 0.7J of energy used) crushed much of the grain into small particles and it was not clearly distinguished from the results over that range (Plate 1). Conclusively, a possible range for the drop height for measuring maize breakage using HT-I drop tester was from 10 to 30 cm. For the main experiment (Chapter 5), the used drop height for breakage testing was 20 cm.

Table 1. The percentage of particles and breakage susceptibility of maize grain using the HT-I drop tester with a flat head metal bar (201.0g) impact.

		Round hole sieve size (mm)			Breakage (%)‡	
		6.35	4.76	Fine	B (6.35)	B (4.76)
		Hmv565-3xE1386 (hard)				
Drop Height (cm)	5	99.08	0.62	0.31	0.92	0.31
	10	85.30	7.91	6.78	14.70	6.78
	15	73.04	12.91	14.05	26.96	14.05
	20	59.78	19.14	21.08	40.22	21.08
	25	46.73	22.70	30.57	53.27	30.57
	35	26.92	23.81	49.28	73.08	49.28
	50	18.24	25.26	56.50	81.76	56.50
		Furio (soft)				
Drop Height (cm)	5	88.59	7.83	3.57	11.41	3.57
	10	71.46	15.40	13.14	28.54	13.14
	15	50.17	20.40	29.43	49.83	29.43
	20	41.35	19.82	38.83	58.65	38.83
	25	32.89	19.00	48.11	67.11	48.11
	35	9.70	21.30	68.99	90.30	68.99
	50	14.22	23.52	62.26	85.78	62.26

‡ Note: B (6.35): Breakage susceptibility measured with 6.35mm (16/64 inch) round hole sieve.
B (4.76): Breakage susceptibility measured with 4.76 mm (12/64 inch) round hole sieve.

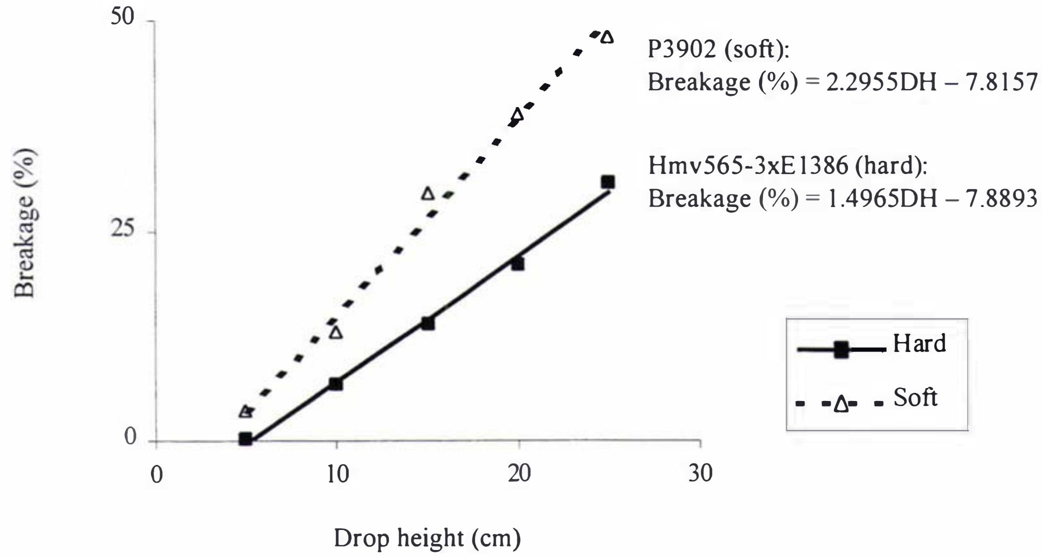


Figure 1. Comparison of the breakage susceptibility of soft and hard maize grain at various drop heights of the flat head metal bar (201.0g).

Note: Breakage susceptibility is expressed as the percentage of particle weight which passed through a 12/64 inch round hole sieve (4.76 mm) per total weight of grain tested. The area of impact weight is 2.01mm^2.

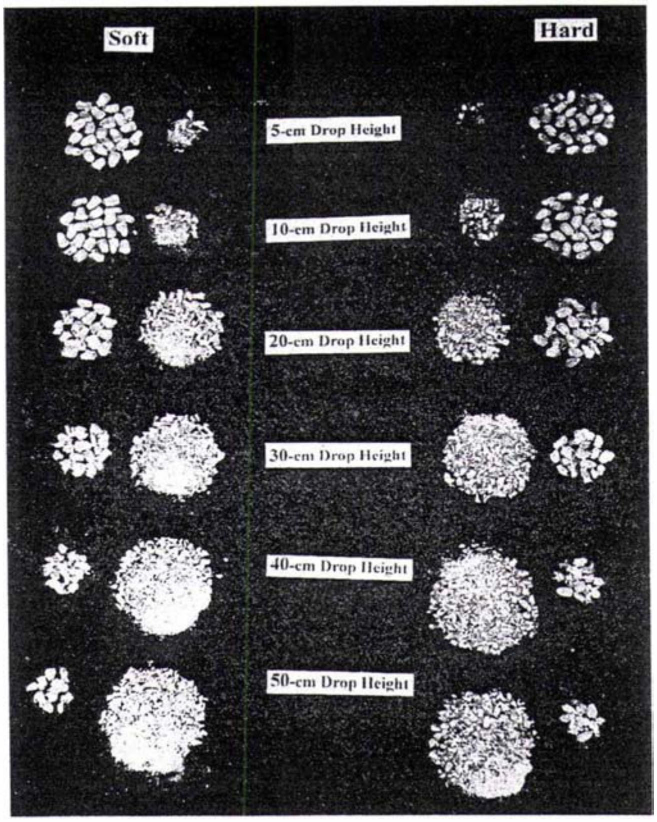


Plate 1. The result of breakage test at various drop height using the HT-I drop tester.