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BREAKAGE SUSCEPTIBILITY OF BLENDED CORN

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Breakage susceptibility of blended corn

by

Vu Thai Nguyen

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Major: Agricultural Engineering

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## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>LITERATURE REVIEW</strong></td>
<td>2</td>
</tr>
<tr>
<td>Properties of Cereal Grains</td>
<td>2</td>
</tr>
<tr>
<td>The size and shape of cereal grains</td>
<td>2</td>
</tr>
<tr>
<td>Anatomy of the mature corn kernel</td>
<td>3</td>
</tr>
<tr>
<td>Drying Grain by Solar-Dried Desiccant</td>
<td>7</td>
</tr>
<tr>
<td>Solar energy grain drying</td>
<td>7</td>
</tr>
<tr>
<td>Economic aspects of solar grain drying and desiccant preparation</td>
<td>8</td>
</tr>
<tr>
<td>Simulation of solar grain drying</td>
<td>11</td>
</tr>
<tr>
<td>Damage Related to Harvesting</td>
<td>12</td>
</tr>
<tr>
<td>Shelling action on ear corn in a grain combine</td>
<td>12</td>
</tr>
<tr>
<td>Damage due to shelling action</td>
<td>14</td>
</tr>
<tr>
<td>Damage Related to Drying</td>
<td>17</td>
</tr>
<tr>
<td>Low temperature drying</td>
<td>17</td>
</tr>
<tr>
<td>The allowable storage time</td>
<td>18</td>
</tr>
<tr>
<td>Stress cracks due to drying</td>
<td>20</td>
</tr>
<tr>
<td>Damage Related to Blending</td>
<td>23</td>
</tr>
<tr>
<td>Equilibrium moisture content</td>
<td>24</td>
</tr>
<tr>
<td>Stress cracks due to blending</td>
<td>26</td>
</tr>
<tr>
<td>Damage Related to Handling Methods</td>
<td>28</td>
</tr>
<tr>
<td>Methods of Detecting Grain Damage</td>
<td>36</td>
</tr>
<tr>
<td>The USDA grading system</td>
<td>36</td>
</tr>
<tr>
<td>Corn breakage testers</td>
<td>37</td>
</tr>
<tr>
<td>Candling method</td>
<td>39</td>
</tr>
<tr>
<td>Colorimetric technique</td>
<td>40</td>
</tr>
<tr>
<td>Visual inspection</td>
<td>41</td>
</tr>
<tr>
<td>Germination tests</td>
<td>41</td>
</tr>
<tr>
<td>Invisible damage detection tests</td>
<td>42</td>
</tr>
<tr>
<td>Economic Aspects of Damage</td>
<td>44</td>
</tr>
<tr>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Test weight discount</td>
<td>45</td>
</tr>
<tr>
<td>Broken corn and foreign material discounts</td>
<td>45</td>
</tr>
<tr>
<td>Damaged kernel discounts</td>
<td>45</td>
</tr>
<tr>
<td>OBJECTIVES</td>
<td>47</td>
</tr>
<tr>
<td>EQUIPMENT, PROCEDURES AND MATERIALS FOR THE EXPERIMENT</td>
<td>48</td>
</tr>
<tr>
<td>Experimental Design</td>
<td>48</td>
</tr>
<tr>
<td>Grain</td>
<td>50</td>
</tr>
<tr>
<td>Moisture Determination</td>
<td>50</td>
</tr>
<tr>
<td>Wet Portion</td>
<td>52</td>
</tr>
<tr>
<td>Dry Portion</td>
<td>52</td>
</tr>
<tr>
<td>Desiccant Corn</td>
<td>55</td>
</tr>
<tr>
<td>Blending of Grain</td>
<td>55</td>
</tr>
<tr>
<td>Stein Breakage Tester</td>
<td>57</td>
</tr>
<tr>
<td>RESULTS AND DISCUSSION</td>
<td>61</td>
</tr>
<tr>
<td>Moisture Content after Storage</td>
<td>61</td>
</tr>
<tr>
<td>Susceptibility to Breakage</td>
<td>68</td>
</tr>
<tr>
<td>Selecting the Blending Ratio</td>
<td>79</td>
</tr>
<tr>
<td>For blending wet corn and dry corn</td>
<td>79</td>
</tr>
<tr>
<td>For blending wet corn and desiccant</td>
<td>82</td>
</tr>
<tr>
<td>Economic Aspects of Blending</td>
<td>84</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>86</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>88</td>
</tr>
<tr>
<td>SUGGESTIONS FOR FURTHER STUDY</td>
<td>89</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>90</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>96</td>
</tr>
</tbody>
</table>
INTRODUCTION

Corn is a major crop in the United States of America. In 1978 alone, the U.S. produced 258 million tons of cereal grains, of which corn accounted for 170 million tons. The U.S. is the largest producer and exporter of corn in the world (U.S. Bureau of the Census, 1978).

Recently, the use of solar energy as an alternative of energy for low temperature grain drying has been a subject of many studies. One solar project involves drying wet corn by blending it with overdried corn. Corn is overdried in the spring and summer with the heat from a solar collector. In the fall, this overdried corn (called desiccant) is blended with wet corn to produce a blend suitable for low temperature drying, storage or marketing (Bern et al., 1980). The moisture cycle changing from wet corn at over 20% moisture to desiccant at under 10% and back to 15.5% or 20% moisture may make corn kernels susceptible to breakage and thereby incur a discount at the time of marketing. Also, in grain trading, farmers often blend dry corn with a moisture content lower than 15.5% with wetter corn to get the blend at 15.5% moisture content prior to marketing.

The consequence of blending of corn in the above ways has not been studied thoroughly. Therefore, this research attempts to study several of the results of blending wet and dry corn.
LITERATURE REVIEW

The modern mechanization of farming methods in production and handling of grain has led to a considerable increase in mechanical damage to the grain during harvesting and subsequent handling. Grain damage is a failure of grain under either excessive deformation when it is forced through fixed clearances or excessive force when it is subjected to impact. Damage to the grain kernels could affect their processing quality and/or result in greater losses in handling (Mohsenin, 1970). Mechanical damage of grain is due either to external forces under static or dynamic conditions or to internal forces.

To study the breakage of blended corn, it is necessary to understand the causes of mechanical damage of grain. Therefore, the following topics will be reviewed in the literature review: properties of cereal grains; damage related to harvesting; drying grains by solar-dried desiccant; damage related to drying, handling, and blending; methods of detecting grain damage; and economic aspects of damage.

Properties of Cereal Grains

To be able to study the breakage susceptibility of blended corn, it is necessary to understand the physical properties of cereal grains—especially of corn kernels—such as size and shape, and the components of the kernel.

The size and shape of cereal grains

The cereals of commerce and industry are harvested, transported and stored in the form of grain. The size of grain is an average size
calculated from 1000 kernels. The length of the kernels varies from 3.0 mm to 17.0 mm and the width varies from 1.5 mm to 15.0 mm. The average weight per 1000 kernels varies from 21 g to 285 g. The corn kernel has a wide variation in size and has the greatest weight compared to other cereal grains. The weight of corn kernels varies among varieties and among the kernels of the same ear of corn. The corn kernels in the midsection weigh more than the kernels at the ends. The dimensions and average weight per 1000 kernels of the cereals are shown in Table 1. The shape of cereal grains is shown in Fig. 1.

Table 1. Dimensions and average weight per 1000 kernels of the cereals (Kent, 1975)

<table>
<thead>
<tr>
<th>Cereal grains</th>
<th>Lengths (mm)</th>
<th>Width (mm)</th>
<th>Average weight (g per 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>8-14</td>
<td>1-4.5</td>
<td>37</td>
</tr>
<tr>
<td>Corn</td>
<td>8-17</td>
<td>5-15</td>
<td>285</td>
</tr>
<tr>
<td>Oats</td>
<td>6-13</td>
<td>1-4.5</td>
<td>32</td>
</tr>
<tr>
<td>Rice</td>
<td>5-10</td>
<td>1.5-5</td>
<td>27</td>
</tr>
<tr>
<td>Rye</td>
<td>4.5-10</td>
<td>1.5-3.5</td>
<td>21</td>
</tr>
<tr>
<td>Sorghum</td>
<td>3-5</td>
<td>2.5-4.5</td>
<td>23</td>
</tr>
<tr>
<td>Wheat</td>
<td>5-8</td>
<td>2.5-4.5</td>
<td>37</td>
</tr>
</tbody>
</table>

Anatomy of the mature corn kernel

The kernel of corn (Zea mays L.) is a fruit composed of a thin pericarp enclosing a single seed. The pericarp is a mature ovary wall and comprises all the outer cell layers down to the seed coat. The seed comprises the seed coat, endosperm and the germ (Fig. 2). The tip cap,
Fig. 1. Grains of the six principal cereals, showing comparative sizes and shapes. The kernels of the three husked grains (barley, oats, rice) are shown in the bottom row (Kent, 1975)
where the kernel was joined to the cob, is usually present, but may sometimes be lost during shelling (Wolf et al., 1952a-d; Brooker et al., 1978).

**Tip cap**  The tip cap is at the extreme base of the kernel and is composed of pedicel tissue which originally joined the kernel to the cob. Usually the kernel separates from the cob at the base of the tip cap. Sometimes, however, the tip cap remains attached to the cob, or is removed by subsequent handling of the kernel. When present on the kernel, the tip cap is easily removed by a slight pull, exposing the dark hilar layer which lies above it, and covers the base of the kernel.

**The pericarp**  The pericarp is the outermost structural part of the kernel except over the relatively small area at the base covered by the tip cap. Tissues of the pericarp and tip cap are continuous; hence, these structures form a complete covering for the seed. Along its inner surface, the pericarp is in direct contact with the seed coat.

The pericarp comprises about 5 to 6% of the weight of the kernel.

**The seed**  The seed comprises the following parts:

--- **Seed coat and hilar layer:** The seed coat lies just inside the pericarp and covers all the kernel except the base. The hilar layer, continuous with the seed coat, covers the basal portion of the kernel. Together, the seed coat and hilar layer form an unbroken protective covering about the entire germ and endosperm.

--- **Endosperm:** The endosperm comprises about 80 to 84% of the weight of the corn kernel. It consists of a thin outer layer of aleurone cells, containing oil and protein and a large inner portion of storage
Fig. 2. Cross section of a corn kernel (Brooker et al., 1978)
tissue which contains starch and protein. The endosperm envelops the germ. Two types of starch storage endosperm are horny endosperm and floury endosperm. The proportion of horny to floury endosperm depends upon the type and variety of corn.

---Germ: The germ or embryo is embedded in the lower portion of the endosperm just beneath the face of the kernel and parallel to its long axis. The germ comprises about 10 to 14% of the weight of the kernel in the different varieties of corn.

The germ has two parts: the embryonic axis and the scutellum. The embryonic axis gives rise to the mature plant and makes up less than 2% of the weight of the kernel. The scutellum is a feeding organ for the germinating embryo. It is much larger than the embryonic axis and comprises roughly 10% of the weight of the kernel.

Drying Grain by Solar-Dried Desiccant

The increasing cost of fossil fuels has encouraged many researchers to consider solar energy as an alternative source of energy for grain drying. Their studies include design of cheap solar collectors, using computers to simulate performance of solar dryers, and storing solar energy in the form of overdried corn and then blending with wet corn. There have also been studies on the economic aspects of its application.

Solar energy grain drying

Solar energy for grain drying has been in use for many thousands of years in many parts of the world. It is commonly called sun drying. In the past, research on solar grain drying progressed slowly because of the
low cost of fossil fuels and rapidly developing dryer technology until the fuel crisis in 1973. Since then, many research studies have been done on the use of simple and inexpensive solar collectors for crop drying. Kline (1977) reported on performance tests of 12 different solar collectors. In his experiments, both air supported and rigid frame collectors were used. Collector absorbing surfaces were of flat and curved designs, both covered and bare, and single air channeled or with suspended absorber plates. Materials included plastic film, rigid plastic, glass, metal and wood. Each collector was 9.1 m long and 0.91 m wide, providing 8.3 m$^2$ of absorber area. All were operated simultaneously and airflow rates were identical to provide comparative data. Incoming solar insolation was measured with a pyrometer to determine relative efficiencies. Collector efficiency for full days of operation ranged from 11 to 57%. The lowest efficiencies were obtained with bare plate collectors. Highest efficiencies were observed for suspended plate collectors with insulated back plates. The high performance collectors could pick up an average of about 93.15 kJ per day per square meter of collector.

Economic aspects of solar grain drying and desiccant preparation

Kranzler et al. (1975) investigated the economic feasibility of a solar heat supplemented low temperature grain drying system using a plastic covered flat plate solar collector. The collector had a polyethylene plastic cover, a black polyethylene absorbing surface and a plywood bottom. No insulation was applied to the back of the collector.
Drying air was drawn in at the ends of the collector and through the air space on either side of the suspended absorber film to the centrally located fan intake. The maximum temperature rise was about 5.6°C. Average daytime efficiency was 40% with maximum approaching 67% at solar noon. From results of drying tests, it was found that solar energy can replace about 19% of the electrical energy requirement of drying. But they also found the value of energy saving will not quite equal the total cost of materials for the collector.

Bern et al. (1980) studied a method for prolonging the use of solar collector on a corn dryer by storing energy in the form of drying capacity in overdried corn. This overdried corn (called desiccant) can be blended with wet corn at harvest to produce a blend suitable for low temperature drying, storage or marketing. The object of the desiccant is to get the corn as dry as possible at minimum energy and collector cost. The lower the desiccant moisture content, the better the blending ratio according to the equation:

\[
\begin{align*}
\frac{r}{(100 - M_d)} &= \frac{(100 - M_b)}{[100 - M_w] - 1} \\
\end{align*}
\]

where:

- \( r \) = blending ratio;
- \( M_b \) = moisture content of blend (wet basis);
- \( M_d \) = moisture content of desiccant (wet basis); and
- \( M_w \) = moisture content of wet corn (wet basis).
In the desiccant system, corn from one year's harvest was overdried during the spring and summer with heat from a solar collector. In the fall, part of the overdried corn was blended with wet, freshly harvested corn to produce a 20% moisture content blend, which was then low-temperature dried to a safe storage moisture content. The rest of the desiccant was blended with wet corn to produce a 15.5% moisture content blend for sale or storage. This system used a solar collector recommended by Kline (1977) with the specifications in Table 2 below.

Table 2. Solar collector specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Fixed, covered, suspended plate, air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>17.8 m²</td>
</tr>
<tr>
<td>Cover</td>
<td>Corrugated greenhouse fiber glass</td>
</tr>
<tr>
<td>Absorber</td>
<td>6.4 mm chipboard, painted black</td>
</tr>
<tr>
<td>Material cost</td>
<td>$17.25/m²</td>
</tr>
<tr>
<td>Labor</td>
<td>3 h/m²</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>30° in summer, 45° in fall</td>
</tr>
<tr>
<td>Airflow m³/s.m²</td>
<td>0.041 in summer, 0.061 in fall</td>
</tr>
<tr>
<td>Max temperature rise °C</td>
<td>12 in summer, 8.9 in fall</td>
</tr>
</tbody>
</table>

The 3-year test of the desiccant system compared with a conventional low-temperature system showed that this system used 31% as much electrical energy and the cost analysis showed annual net cost per unit of capacity for the desiccant system was about 5% less than that for a conventional low temperature system, used as a control.

The broken corn and foreign material levels in two loads of marketed blended corn in field tests in 1980 were 2.0% and 0.62%.
These loads were blended desiccant at moisture content of 8.97% and wet corn at 21.41%. Blend moisture content was 13.9% after 48 hours stirring, 30 hours aeration and 42 days storage.

**Simulation of solar grain drying**

With the aid of computers, simulation models for grain drying were developed for predicting the performance of solar grain dryers and grain drying systems.

Morey et al. (1977) studied the effect of supplemental solar heat on airflow rates and reduction in fossil fuel, as well as the economic feasibility of supplemental solar heat drying, by simulating the drying process using long-term weather records. They found that supplemental heat did not significantly reduce dry matter decomposition in the top layer of grain in most years. It generally reduced the minimum required airflow rate 10 to 15% compared to ambient air drying. Providing supplemental solar heat for low temperature drying did not appear to be economically feasible at that time.

Thompson and Pierce (1978) used a computer simulation model to compare possible advantages of solar energy in grain drying over other low temperature grain drying modes. Their results showed that in most locations, supplemental heat of approximately 1.1°C above ambient temperature from the drying fan did not significantly reduce the required airflow rate.

Anderson et al. (1980) developed a program to study overall drying system characteristics of the combination desiccant low temperature
system for drying corn with solar heat which was described by Bern et al. (1980). In this program, they used a simulation model which was a modified Thompson's natural air model, a 23.8 m² flat-plate collector, 4.6 m corn depth and 85% fan efficiency. They found with 15% initial moisture content corn, dried to 8.5% final moisture, the airflow rate should be 0.014 m³/s·t and 3 t/m² of collector area should be used (for the year 1976). They also found the cost to remove a unit mass of water decreased as the grain-mass/collector area ratio increased.

Damage Related to Harvesting

The primary cause of mechanical damage to grain is the field shelling operation. The nature of damage is mostly physical damage as indicated by many research workers. To understand the theory of shelling and what happens to the corn cob in the shelling crescent will be helpful in a study of internal cracking of corn and of breakage susceptibility of blending wet and dry corn.

Shelling action on ear corn in a grain combine

High speed movies show that an ear of corn is presented to the shelling mechanism in one of three positions. The ear is perpendicular to the cylinder axis, or the ear is parallel to the cylinder axis or the ear is at an angle between the above two positions (Waelti, 1967).

(1) The ear of corn is oriented perpendicular to the cylinder axis. The first contact between the ear and the cylinder concave is when the raspbar of the cylinder delivers an impact blow to the ear while it is still located on the solid feed plate located at the front of the
shelling crescent. The impact blow of the raspbar drives the struck kernels into the cob and severely damages them. The kernels located on each side of the blow are shelled either by the impact blow or by the sideward forces developed as the wedge-like corn kernels are driven into the cob. The rear motion of the ear, after impact, continues as the raspbar passes beyond the ear and is followed by succeeding raspbar strikes on the ear. The second impact of the perpendicular oriented ear is about 2.5 to 5 cm in front of the last impact. Each bar passes over the ear and succeeding bars continue to strike the ear until it is rolled or swept out of the shelling crescent.

(2) The ear of corn is parallel to the cylinder axis. In this case, the raspbar strikes the ear a broadside blow that lies between a radial and tangential blow and then passes over the ear, raking off kernels located rearward of the strike area. The raspbar is followed by a filler plate. The filler plate bar impacts a rotary motion to the ear that causes the ear to roll rearward and at the same time increasing the force on the kernel of the corn. This rolling action loads the kernels next to the filler plate and the concave bar and forces shelling in the adjacent rows. The succeeding raspbar impacts against the ear as the filler plate rotates rearward. Under a rolling condition, the angular velocity of the filler plate is twice as fast as that of the ear. This causes the ear to be passed to the succeeding raspbar as it is rolled under the pushing of the filler plate and the raspbar.

The detachment force (Fig. 3) required to break the rachilla and the glume kernel friction can be expressed as follows:
\[ F_D = kA\tau_R + F_G \]

where:

- \( F_D \): detachment force, N;
- \( k \): constant related to the method of force application;
- \( A \): cross sectional area of rachilla, m\(^2\);
- \( \tau_R \): failure stress in rachilla, N/m\(^2\); and
- \( F_G \): friction force between glumes and kernels, N.

The value of the constant \( k \) depends on the direction of the detachment force \( F_G \) (Waelti, 1967). There are three main directions of force application:

- Axial direction of kernel, \( F_N \).
- Axial direction of the cob, \( F_L \).
- Tangential direction of the cob cross section, \( F_T \).

The detachment force \( F_D \) requirement was measured experimentally (Johnson and Lamp, 1966). The smallest detachment forces were required by pulling the kernels in tangential direction \( F_T \) and in the axial direction of the cob \( F_L \). The largest detachment force was in the axial direction of the kernel \( F_N \).

**Damage due to shelling action**

Fox (1969) used high speed photography to study the shelling operation of corn. He observed that an ear of corn was subjected to about seven to nine impacts against the raspbars of the combine cylinder before the kernels were shelled from the cob, and this caused mechanical damage to the crown of the kernel. After the shelling was complete, only
Fig. 3. Detachment force analysis
a portion of the kernels passed immediately through the concave; the others bounced for some time between the cylinder and concave. During this period, the kernels were subjected to high and low impacts from the shelling unit and compressive loading from the incoming ears, thus causing further mechanical damage to the kernels.

Brass (1970) used high speed photography with both a roller sheller and conventional cylinder type shelling, and found that, in both machines, only a part of the detached kernels passed through the concave. The rest rebounded and were driven back toward the concave by the rasp-bars for 7 to 12 rebounds for the most damaged and battered kernels.

Ayres et al. (1972) found that the mean mechanical damage of combined corn was 34.4% in a typical field harvesting system in Iowa, depending on the crop condition, machine setting and machine operator. The damage consists of 5.1% visual damage, 3.0% hidden damage class I and 26.3% hidden damage class II. The visual damage was defined as "less than whole" kernels. Hidden damage was detected by fast green dye; hidden damage class I represented damaged kernels easily visible without close examination. Hidden damage class II represented hairlike cracks, small chipped areas, and tip damage.

Kline (1973) did an analysis on mechanical damage related to harvesting for 500 shelled corn samples. The moisture content of the shelled corn samples ranged from 16.3 to 32% wet basis. Seven makes of combines of various sizes and one picker-sheller were used. Combine cylinder speeds ranged from 375 to 800 rpm. In this survey, the concave clearance of the combine was set in the rear narrower than the front
of the cylinder. He found that the average broken corn and foreign material was 0.6%. Damaged kernels (moldy, diseased, heat damaged, etc.) were less than 1% of the weight of the samples.

Mahmoud and Buchele (1975) reported that the mean for mechanical damage of corn increased from 15% at concave inlet to 45% past the concave extension due to the repetitive impacts from the raspbars of the cylinder as ears and shelled kernels travelled down the shelling crescent. A kernel was considered damaged if it was broken, cracked, chipped, had bruised pericarp, or had any hairline crack in the pericarp.

Chowdhury and Kline (1978) studied internal and external damage to corn kernels from the combine cylinder. They found that the overall mean was 40% for total external damage (pericarp injury) and 26% for internal damage (stress crack).

Damage Related to Drying

The purpose of grain drying is to reduce the growth of molds and prolong the period of storage. The method of drying will affect the quality of grain. Low temperature drying is restricted by allowable storage time. High temperature drying may increase stress cracking of grain and then affect breakage susceptibility in subsequent blending and handling.

Low temperature drying

Low temperature or natural air drying is a process of slow drying with natural air or air that is heated a few degrees from 1.1 to 5.6°C.
Drying rate depends on the relative humidity of air and the airflow rate. The minimum airflow rate is about 0.018 m$^3$/s.t. The lower the relative humidity of the air, the higher the drying rate. Supplemental heat normally comes from the heat that is produced by the fan motor and as fan power increases, the heat added to the air increases. Heat can also be obtained from a solar collector. Broken grain and foreign material increase resistance of air flow by concentrating under the spout. The effect of screening corn on the deterioration rate of shelled corn was studied by Kalbasi et al. (1979). Cleaning the grain and using a spreader will minimize this problem. Stirring devices in low temperature systems can increase the airflow and reduce overdrying, but will increase costs and breakage of grain (MWPS 22, 1980). The drying period for low temperature drying extends over several days or weeks. For this reason, most systems are designed for one batch of drying per harvesting season. Low temperature drying is applicable only in those geographic regions where average daily temperatures are low during the harvest period.

The allowable storage time

The data of allowable storage time for corn of different initial moisture contents and temperatures was developed by Steele et al. (1969). This graph (Fig. 4) allows grain managers to determine how long they would store grain at certain conditions before spoilage occurs. Steele et al. (1969) predicted the deterioration of shelled corn by measuring the carbon dioxide production in small samples of corn. This carbon
Fig. 4. Allowable storage (drying) time for shelled corn at various temperatures and moisture contents. Data from the U.S. Department of Agriculture Grain Storage Research Laboratory, Ames, Iowa (Shove, 1981)
dioxide production was related to time, temperature, moisture content and mechanical damage. They suggested an allowable dry matter loss of 0.5% for field shelled corn. A mechanical damage content of 30% was typical of shelled corn harvested at 28% moisture. The mechanical damage was defined as the weight of broken kernels over the total weight of the sample.

The permissible storage time for aerated shelled corn at 30% mechanical damage and at various moistures and temperatures was computed, based upon an allowable dry matter loss of 0.5%, by the following equation:

\[ T = T_R \times M_T \times M_M \times M_D \]

where:

- \( T \) is the estimated allowable exposure time before 0.5% of dry matter has been consumed, hours; and

- \( T_R \) is the time that results in loss of 0.5% dry matter at 15.5°C with 25% moisture, 30% mechanical damage corn, hours.

- \( M_T, M_M \) and \( M_D \) are multipliers for temperature, moisture and damage, respectively. These values could be read from the graphs (Figs. 5-8) based on experimental data.

Steele et al. (1969) also developed correction constants for corn under different conditions of moisture content, damage and temperature.

**Stress cracks due to drying**

Thompson and Foster (1963) studied stress cracks and breakage in artificially dried corn and found that shelled corn dried with heated
Fig. 5. Moisture multiplier as a function of moisture content (Steele et al., 1969)

Fig. 6. Temperature multiplier as a function of temperature (Steele et al., 1969)
Fig. 7. Mechanical damage multiplier as a function of mechanical damage (Steele et al., 1969)

Field shelled corn
--30% mechanical damage
--0.5% dry matter loss
Moisture content, % w.b.

Fig. 8. Permissible storage time with temperature, moisture content and mechanical damage based on the adjusted moisture multiplier (Steele et al., 1969)
air was two or three times more susceptible to breakage than the same corn dried with unheated air. They also observed that corn dried from 30% moisture to 15.5% was more susceptible to breakage than that dried from 20%. As the drying air temperature and airflow rate were increased, the shelled corn became somewhat more susceptible to breakage.

Foster (1968) reported that high speed and high temperature drying may damage grain or contribute to grain damage in several ways. Rapid drying leads to increased brittleness of the grain. Stress cracks or endosperm fissures are formed during heat drying and/or subsequent cooling. The stress cracks or fissures made the grain more susceptible to breakage during handling. The breakage was more severe in corn than in other grains.

Ross and White (1971) studied stress cracking in white corn dried with heated air as affected by various initial and final moisture contents. They found that stress cracking increased as the temperature increased from 54 to 104°C and that corn dried to final moisture levels of between 10 and 14% moisture had 70 to 90% cracked kernels.

Damage Related to Blending

Farmers often blend dry corn with the moisture content lower than 15.5% with the wet corn to get the blend at 15.5% moisture content prior to marketing. Farmers do not receive premiums on grain that is too dry, but they will get a discount if the moisture of corn is above 15.5%. The blending is simply done when the corn is unloaded from the bin prior to transport to the elevator (Hoffman, 1980). The moisture from the wet grain in the blend will be absorbed by the dry grain until the two
fractions reach an equilibrium moisture content. An understanding of this phenomenon and the effects of blending grains of two different moistures will be necessary to a study of the breakage susceptibility of blended corn.

**Equilibrium moisture content**

Each grain kernel has different water vapor pressure at a certain temperature and moisture content. The grain kernel will desorb (lose) or absorb (gain) moisture when exposed to moist air until its pressure is equal to the water vapor pressure of the surrounding air. The equilibrium moisture content is dependent upon the humidity and temperature conditions of the environment as well as the species, variety and maturity of the grain. The values of desorption moisture contents are higher than the adsorption values.

By maintaining constant temperature and finding equilibrium moisture content of grain for various humidities of ambient air, a curve of equilibrium moisture content against relative humidity of ambient air may be established (Fig. 9). Such curves are known as desorption and adsorption isotherms. The difference between the desorption and adsorption isotherms is called the hysteresis effect. The magnitude of the desorption isotherm is related to the conditions encountered in drying grain and the adsorption isotherm is relevant in considering storage problems where dry grain may receive moisture from a humid atmosphere.

There are a number of theoretical, semi-theoretical and empirical models for calculating the moisture equilibria of cereal grains. But
Fig. 9. Equilibrium moisture content, yellow dent corn (Agric. Engr. Yearbook, 1981)
no equation is capable of predicting accurately the moisture equilibrium contents of cereal grains over the full temperature and relative humidity ranges (Brooker et al., 1978). The understanding of moisture movement in a mass of grain will help to explain the drying process and the equilibrium moisture of blending cereal grains. Table 3 shows the difference between desorption and adsorption moisture contents for corn at 22°C (Chung and Pfost, 1967).

<table>
<thead>
<tr>
<th>Relative humidity %</th>
<th>Desorption % moisture</th>
<th>Adsorption % moisture</th>
<th>Difference % moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.5</td>
<td>24.2</td>
<td>23.4</td>
<td>0.4</td>
</tr>
<tr>
<td>67.6</td>
<td>16.5</td>
<td>15.2</td>
<td>1.3</td>
</tr>
<tr>
<td>46.5</td>
<td>12.9</td>
<td>11.5</td>
<td>1.4</td>
</tr>
<tr>
<td>25.8</td>
<td>9.8</td>
<td>8.0</td>
<td>1.8</td>
</tr>
<tr>
<td>9.4</td>
<td>7.0</td>
<td>5.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Stress cracks due to blending**

Kunze and Hall (1965) made the hypothesis for rice, that fissures are caused by moisture adsorption. They said that this may happen because moisture adsorbed by the external cells causes these cells to expand and produce compressive stresses in the surface layers of the kernel, which itself acts as a free body. Therefore, opposite stresses must be produced elsewhere in the grain causing fissures.

Hart (1967) found that, when overdried corn was mixed with undried
corn to produce a mean moisture content of 15.5%, the mixture was more likely to become moldy than unmixed samples at the same moisture level. In addition, the moisture of neither of the two fractions ever reached the average moisture content; the moisture of the mixture remained nearly constant from the third day.

Brekke (1968) studied stress crack formation as an effect of rewetting low-moisture corn. The effect of the initial moisture content of corn on rewetting was investigated over a range of 10 to 20% at 24°C. Tempering corn with an initial moisture content of 20.1% produced no stress cracks in a 6-h period. For 14.6% corn, almost 50% of the kernels developed stress cracks in 2 h. The rate of stress crack formation showed further increases as initial moisture of corn was lowered from 13.5 to 10.1%. The effect on stress crack formation of rewetting 13.4% initial moisture content corn at 24°C to moisture levels of 15, 16, 18, and 21% showed that no stress cracks developed with the 15% moisture, but they gradually increased as moisture levels were progressively raised to 21%. With the 21% moisture, approximately 60% of the kernels had stress cracks after 2 h.

White and Ross (1971) blended dry corn at 8% and wet corn at 23% moisture. The mixtures were held at different temperatures from 4 to 38°C without aeration or further disturbance for 8 days. The moisture of the mixture did not change from the third day, and the moisture difference between the two fractions remained at 1.7 to 3.4 points.

Kunze and Prasad (1978) studied grain fissuring potentials in harvesting and drying of rice. They blended low moisture rice with
high moisture rough rice in a sealed container for 48 h and found that low moisture rice will fissure when it is subjected to an environment from which it can rapidly adsorb moisture.

Damage Related to Handling Methods

The modern mechanization of farming methods has led to a considerable increase in the bulk handling of grain. Mechanical handling equipment plays an important role in the bulk handling process. Much of the damage is due to the impact of grain against some object. Damage related to handling will contribute to the total breakage after blending at the elevator.

Louvier and Calderwood (1972) determined the amount of breakage from dropping milled rice from various heights onto other rice, concrete and steel. The breakage resulted from dropping rice onto the steel was highest, and from rice onto rice was lowest. By inclining the steel or concrete impact surface to 45 degrees, breakage was reduced approximately 60%. Breakage increased with drop height up to 18 m. Breakage was significantly higher in rice at 11% moisture than in rice at 13% moisture content.

Fiscus et al. (1971) simulated most typical handling techniques in the laboratory. They simulated dropping grain into a storage bin, into an empty bin, and into a partially filled bin. They found that dropping grain from heights greater than 12 m caused more breakage than any other handling system. Corn incurred more breakage than soybeans and soybeans more breakage than wheat. Breakage was greater at low grain moistures and temperatures.
Sands and Hall (1971) found that a screw conveyor with a diameter of 15 cm caused only a very small amount of damage to dry shelled corn at 13% moisture content when operated at full capacity, but the level of damage increased greatly when the conveyor was kept at one-fourth capacity. Kernels were considered to be damaged if they were split, cracked or broken or if they had nicks which penetrated the seed coat and exposed the endosperm or germ. Kernels were not considered damaged if just the tip cap was missing. Each test consisted of 15 runs or cycles at full capacity, simulating 45.72 m of screw conveyor and 15 runs at one-fourth capacity. At full capacity, the conveyor caused damage equivalent to 0.035 m$^3$ of damaged kernels per 353 m$^3$ of corn per 30.4 m of conveyor, compared with 0.6 m$^3$ of damaged kernels at one-fourth capacity. As the screw speed was increased, the level of damage increased. At 865 rpm, the damage was 5 times greater than at 275 rpm. The conveyor caused less damage to corn at 22% moisture content than at 13% moisture.

Stephens and Foster (1976) tested the effect of drying treatment on the breakage due to handling by using three different types of drying such as field drying, drying at 38 to 54°C and at 93 to 104°C. For the test run, the corn was removed from a storage bin, elevated and dropped through a spout into a truck (Fig. 10). They found a good correlation between the breakage determined by the Stein tester in 4 minutes and the actual breakage due to handling. The summary of results and the ratio between Stein tester breakage and actual breakage are derived in Table 4.
Fig. 10. Flow path of corn through feed elevator to the truck (Stephens and Foster, 1976)
Table 4. Summary of Stein tester breakage and actual breakage due to handling and related to drying treatment (derived from Stephens and Foster, 1976)

<table>
<thead>
<tr>
<th>Drying treatment</th>
<th>Number or tests</th>
<th>Range moisture content %</th>
<th>Range tester breakage %</th>
<th>Range actual breakage %</th>
<th>Ratio tester/actual</th>
<th>Standard deviation of ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dried in field</td>
<td>11</td>
<td>13.0-13.7</td>
<td>2.1-4.6</td>
<td>0.6-1.2</td>
<td>3.85</td>
<td>0.98</td>
</tr>
<tr>
<td>Dried at 38-54°C</td>
<td>12</td>
<td>12.2-12.9</td>
<td>7.9-16.2</td>
<td>1.8-3.4</td>
<td>4.74</td>
<td>0.66</td>
</tr>
<tr>
<td>Dried at 93-104°C</td>
<td>12</td>
<td>11.1-11.8</td>
<td>28.8-43.7</td>
<td>4.2-7.5</td>
<td>6.45</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Stephens and Foster also conducted a second series of tests. They used three different batches of corn. Two batches labeled A and B had been dried in a bin with unheated air. The third batch labeled C was obtained from the commercial stocks. The facility to carry out the handling test was the same as the previous test (Fig. 10). Breakage due to handling was determined by taking the sample before and after the handling. The initial sample from each handling test was used for the breakage tester in a 4-minute test duration to predict the breakage susceptibility of each test lot. They also found a good correlation between actual breakage and Stein tester breakage. The summary of results and the ratio between Stein tester breakage and actual breakage are derived in Table 5.

Martin and Stephens (1977) studied broken corn and dust generated during repeated handling. Fig. 11 shows a schematic drawing of the grain handling system at the U.S. Grain Marketing Research Center where the test was conducted. Corn was moved back and forth between bin 1 and bin 2. Bin 1 was about 20 m deep and 3 m square and had a hopper bottom.
Table 5. Summary of Stein tester breakage and actual breakage due to handling (derived from Stephens and Foster, 1976)

<table>
<thead>
<tr>
<th>Corn lot</th>
<th>Flow rate m³/hr</th>
<th>Range of moisture content %</th>
<th>Range of tester actual breakage %</th>
<th>Ratio of Stein tester deviation actual %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>28.3</td>
<td>13.0-13.2</td>
<td>5.6-12.9</td>
<td>0.8-1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>49.5</td>
<td>13.0-13.5</td>
<td>5.9-10.7</td>
<td>1.5-2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>28.3</td>
<td>10.9-11.4</td>
<td>17.7-26.1</td>
<td>2.1-4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>49.5</td>
<td>12.1-12.3</td>
<td>15.9-21.0</td>
<td>2.8-3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

that discharged from its center. When the corn was moved from bin 1, it fell by gravity through spouts and entered the boot on the descending side of the bucket elevator. It was then elevated 53 m and discharged into another spout. It descended 3 m into and through an automatic grain sampler, descended 1.5 m to a hopper and then continued 3 m to a distributor that directed the flow to bin 2. It then descended another 4.6 m to the point where it entered the receiving bin and fell to the bottom of the bin. Bin 2 was about 26 m deep and 6 m in diameter. It had a sloping bottom that discharged at the side of the bin onto a belt conveyor. From the belt, the grain descended 3 m to enter the elevator boot. The flow path from the bucket elevator to bin 1 was similar to the path described above. They found that the amount of accumulated breakage in the corn increased with each transfer from one bin to another. The level initially 2.0%, increased about 0.6% with each handling, reached a level of 15.7% during the 21st handling.

Paulsen and Hill (1977) studied corn breakage in overseas shipments. They found that in the shipment of U.S. No. 3 and No. 4 shelled
A - 3 sq. meter grain bin, 20 m tall
B - distribution tube
C - 53 m bucket elevator
D - 3 m distribution tube
E - grain sample
F - 1.5 m distribution tube
G - hopper
H - 3 m distribution tube
I - distributor
J, K - 4.6 m distribution tube
L - 6 m diameter grain bin, 26 m tall
M - distribution tube
N - belt conveyor

Fig. 11. Grain flow paths for repeated handling test (Martin and Stephens, 1977)
corn from Toledo, Ohio, to Rotterdam, Holland, average broken corn and foreign material (BCFM) increased from 3.6% to 15% when BCFM was measured by a screening method, and from 18 to 26% when measured by a Stein breakage tester for 2 minutes. For the shipment of U.S. No. 2 shelled corn from Peoria, Illinois, to Mexico, average BCFM increased from 1.2 to 5.3% when measured by screening method, and from 3 to 10% range when BCFM was measured by a Stein breakage tester for 2 minutes.

Stephens and Foster (1977) studied the reduction of damage to corn handled through gravity spouts by using flow retarders and cushion boxes to reduce the impact. They used different dried corn treatments with different types of flow retarders. They found that the use of flowretarding devices to limit grain velocities reduced handling damage, but by a relatively small amount. They also found that the drying treatment had a greater effect on the broken level than did the type of flow retarder. The broken corn was defined as fines passing through a 4.76 mm round hole sieve. The broken corn increase per handling for high temperature drying at 90-100°C was 5.87%. For drying at 50-60°C, broken corn was 2.66%. For field drying, broken corn was 0.92%. The broken corn increase per handling for different flow retarders varied from 5.04 to 6.61% for high temperature drying, from 2.25 to 3.47% for drying at 50-60°C, and from 0.66 to 1.19% for field drying.

Herum and Hamdy (1981) evaluated the capability of several testing combinations to predict corn breakage resulting from passage through a typical full-scale grain elevator. Fig. 12 shows a schematic drawing of the grain handling system. This elevator was considered to be
A - 4.8 m diameter grain tanks, 12 m tall
B - 11.7 m horizontal 3 m U-tube auger
C - 5.7 m horizontal 3 m U-tube auger
D - 22.5 m bucket elevator
E - 8.1 m distribution tube, 45° from horizontal
F - Cleaner
G - 6 m distribution tube, 45° from horizontal
H - 10.8 m bucket elevator
I - 6 m distribution tube, 55° from horizontal
J - 11.1 m horizontal 3 m U-tube auger

Fig. 12. Flow path of corn through feed elevator at each pass from A1 to A2 or reversed (Herum and Hamdy, 1981)
representative of a smaller commercial elevator. Shelled corn was cycled through for eight passes, commencing from a 213 m³ outdoor hopper bottomed tank, carried laterally in a U-tube auger, lifted 22.9 m in a bucket elevator, passed through a separator to remove the screenings, gravity fed into a shorter bucket elevator and finally dropped into another 213 m³ outdoor tank. Actual corn breakage was measured in a feed processing elevator. Samples were withdrawn after each pass to evaluate possible changes in breakage susceptibility due to the extent of handling, as measured by the three testers used; namely, Stein CK-2M (4 min. test duration), the modified Stein, and the centrifugal impact tester. The samples of unbroken corn removed at each pass in the elevator were rescreened over the 6.35 mm sieve before being subjected to laboratory tests. They found the ratio between breakage tester breakage and actual breakage due to handling to be about 10 to 1.

Methods of Detecting Grain Damage

Grain damage can be divided into two categories—external and internal damage. There are different methods of evaluating grain damage depending on the ultimate use of the grains. The following are the different methods that are being used for the evaluation of grain damage in the grain trade and by research workers.

The USDA grading system

The quality of corn in the trade channels, both for domestic use and foreign export, is determined by the USDA grain grading system. This system is based on minimum test weight, maximum moisture content, maximum
broken corn and foreign material, maximum damaged kernels as in heat damage. It consists of numerical grades from number 1 to number 5 and sample grade. Table 6 shows the numerical grades and sample grade requirements for corn.

Table 6. Numerical grades and sample grade\(^a\) and grade requirements for corn (USDA, 1970). Includes the classes yellow corn, white corn, and mixed corn

<table>
<thead>
<tr>
<th>Grade</th>
<th>Minimum test weight per bushel (lb)</th>
<th>Moisture %</th>
<th>BCFM %</th>
<th>Total %</th>
<th>Heat damaged kernels %</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>56</td>
<td>14.0</td>
<td>2.0</td>
<td>3.0</td>
<td>0.1</td>
</tr>
<tr>
<td>No. 2</td>
<td>54</td>
<td>15.5</td>
<td>3.0</td>
<td>5.0</td>
<td>0.2</td>
</tr>
<tr>
<td>No. 3</td>
<td>52</td>
<td>17.5</td>
<td>4.0</td>
<td>7.0</td>
<td>0.5</td>
</tr>
<tr>
<td>No. 4</td>
<td>49</td>
<td>20.0</td>
<td>5.0</td>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>No. 5</td>
<td>46</td>
<td>23.0</td>
<td>7.0</td>
<td>15.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

\(^a\)Sample grade shall be corn that (a) does not meet the requirements for any of the grades from No. 1 to No. 5, inclusive, (b) contains stones, (c) is musty, sour or heating, (d) has any commercially objectionable foreign odor, or (e) is otherwise of distinctly low quality.

USDA grain grading does not account for all kinds of kernel damage that occurs during harvesting, drying and handling. Farmers do not receive premiums on grain that grades better than the standard trading set up by USDA. There is much controversy on USDA grading about test weight and BCFM. Changes in standards are being studied.

**Corn breakage testers**

These testers cause breakage due to impact by a rotating impeller in test chamber for a specific time. The impeller is made of rubber (Cargill grain breakage tester Model No. 2) or steel (Stein grain breakage tester, Model CK-2). Comparing two different impeller materials,
McGinty (1970) found that the steel impeller had a greater consistency. Steel impeller testers were used by Thompson and Foster (1963), Stephens and Foster (1976), Miller et al. (1979). The damage of corn is established as a percent by weight of fines passing through a 4.76 mm round hole sieve. The breakage of grain varies with moisture content, variety and temperature (Herum and Blaisdell, 1981). Many researchers used conventional or modified Stein testers to measure the degree of stress cracking due to field harvest, drying and handling methods (Thompson and Foster, 1963; Stephens and Foster, 1976; Herum and Hamdy, 1981).

Stephens and Foster (1976) found that there was a good correlation between breakage due to handling and predicted results from the Stein tester. However, the procedures used by the researchers differed, since there were no standard test procedures. It is, therefore, difficult to have a conclusion for predicting breakage due to drying and handling. The results of the researcher are only satisfactory for specific conditions under which the tests are based.

For the test duration with Stein instruments, some researchers used 2-minute tests, but most researchers used 4-minute tests as adopted for the 1979-1980 CK-2M correlative study (Herum and Blaisdell, 1981). In the 1980-1981 CK-2M study, 2- and 4-minute tests were studied. With the market grain at 13.0% moisture content, BCFM of 2-minute tests was 70% of BCFM for 4-minute tests with no appreciable difference in coefficient of variation. With the sample at 13.6% of moisture, the BCFM for the 2-minute tests was 67% of those for 4-minute tests.

The moisture content of samples has a great effect on breakage
susceptibility using the Stein model. The breakage increased with decreasing moisture content of corn (Miller et al., 1979; Herum and Blaisdell, 1981). Small changes in moisture content within the range of 12 to 14%, representing much of the corn in markets, corresponded with large differences in indicated breakage susceptibility.

Thompson and Foster (1963) reported that when the temperature of samples of corn was reduced from 29° to 5°C, the amount of breakage doubled. When breakage tests are used to indicate the breakage expected when the corn is handled, the moisture level and temperature should be representative of the lot of corn under consideration.

**Candling method**

The candling method was used by Thompson and Foster (1963) to determine internal stress cracks during drying. The device consisted of a 150 watt incandescent light enclosed in a box with a small square glass-covered hole. The kernels were held over the hole, with the embryo side toward the light source. Samples usually contained from 130 to 150 whole kernels of corn and took 15 or 20 minutes to inspect. As the sample was inspected, the kernels were placed into one of three stress crack categories: single, multiple and checked. The percent of kernels in each category was then computed. This method was used by Brekke (1968), Ross and White (1971) and Hamilton et al. (1972) for evaluation of stress cracks in corn kernels due to rewetting and blending. Kunze and Hall (1965), Kunze and Prasad (1976), and Kunze (1979) used this technique for evaluation of stress cracks in rice due to drying.
Colorimetric technique

Chowdhury and Buchele (1975a) developed a fast technique to evaluate grain damage. They used a dye that will adhere only to the exposed area of the damaged grain and not to the seed coat. After soaking the kernels in this dye, they used a solvent that will leach the dye sticking to the damaged part of the grain. After that, they measured the amount of dye by using some colorimetric techniques that correlated with the amount of damage in the sample. The procedure for spectrophotometric evaluation of mechanical damage grains has the following steps:

1. Immerse the grain sample for 30 seconds in 100 mL + 0.1% Fast Green FCF dye solution (pH = 3.0).
2. Drain the dye and rinse the sample under running tap water for 30 seconds.
3. Immerse and stir the dye sample for another 30 seconds in 250 mL of 0.05 N sodium hydroxide solution.
4. Collect 25 mL of the extracted dye solution and add to 75 mL of distilled water.
5. Pour the diluted extracted dye solution into a 25-mL glass cell and place the cell into the spectrophotometer.
6. Read the damage index (total exposed damaged surface area) on the dial of the spectrophotometer at 610 nm.

The experimental procedure that is outlined above is for a 100 g corn sample. The same principles can be followed for 125, 250 or 1000 g samples of corn or other grains.
Visual inspection

Visual inspection is one of the most reliable methods for measuring mechanical damage of corn. Visual inspection can be either quantitative visual inspection or qualitative visual inspection. In quantitative visual inspection, mechanical damage is the percentage of damaged kernels over the total weight of sample. Damaged kernels ranged from severe damage to hairline cracks. The precision of this method is affected by human judgment. This method was used by Saul and Steele (1966) and Steele (1967).

Qualitative visual inspection is based upon the nature and extent of damage inflicted upon the corn kernels, and damaged corn samples are divided into classes according to the severity of damage. Brass (1970) suggests four major classes of mechanical damage: severe damage, embryo damage, crown damage and pericarp damage. Mahmoud and Kline (1972) divided mechanical damage in corn into five types: BCFM, visible damage, BCFM and visible damage, hidden damage and breakage tester breakage. Chowdhury and Buchele (1976) used visual inspection to develop a numerical damage index for grain damage.

Germination tests

This method provides an excellent method for seed quality evaluation. The tests vary in procedures and objectives. Some examples are:

1. Standard germination tests which are used mainly by seed producers to determine seed quality and viability (Chowdhury and Buchele, 1976).
(2) Cold germination tests are used to evaluate seed quality and seedling vigor. Clark et al. (1969) used this method on mechanically damaged cotton seed.

(3) The acid germination test in which the seed is soaked in sulphuric acid solution (50%) for three hours at 21°C. Then the seed is washed in running water, steeped in 2% calcium carbonate for 15 minutes and again washed with water before being allowed to germinate. Arnold (1964) used this method to evaluate mechanical damage in barley.

(4) Seedling growth rate tests are used by seed laboratories to evaluate seed quality. The seeds are placed in a dark germination chamber at 25°C±1°C for seven days. After germination, the seedlings are dried at 80°C for 24 hours, then weighed, and the total dry weight of the normal seedlings per batch is divided by the number of seedlings included to calculate a seedling growth rate. Seedling emergence tests on commercial corn seed were made by Koehler (1957). Chowdhury and Kline (1976) used this technique to evaluate the effect of internal damage on corn kernels from compression loading.

**Invisible damage detection tests**

Internal damage of grains is very hard to detect. Many researchers used the following methods to detect stress cracks and internal injuries.

**Topographical tetrazolium test** The test was developed by Lakon (1949). For this test, the seed was cut longitudinally and the embryo
was stained with a 1% aqueous solution of 2,3,5-triphenyl tetrazolium chloride. The chemical reacts with an enzyme, supposedly present only in the live embryos, causing a red coloration of the embryo. Chowdhury and Buchele (1975b) used this method to measure damage in corn shelled by the rubber sheller.

**Chemical test** Waelti (1967) reported that the Agricultural Marketing Service of the U.S.D.A. developed a chemical test for damage detection. In this test, an indicator solution of 100 mg iodoxyl acetate, 25 mL ethanol and 75 mL distilled water was used. After immersion of the seeds in this solution, they were exposed to ammonium hydroxide fumes, and within a minute cracked seeds turned blue. This method was used for legume seeds.

**X-ray method** X-ray method has been applied to check for internal damage. Chung and Converse (1968) used this method to investigate the effect of variety and method of harvesting (hand and combine) on the formation of single and multiple stress cracks on wheat kernels.

**Photo-electric method** Christenbury (1975) developed a photo-electric measuring system for measuring mechanical damage of corn, by using a solution that contains 8-anilino-1-naphthalene sulfuric acid. The sample after treatment was ground and was exposed to ultraviolet light. The induced fluorescence was measured with a light sensitive measuring system and related to the mass damage of the grain.

**Photo-elastic and numerical technique** Arnold and Roberts (1969) conducted a method which allows the determination of stress on wheat grain. By using photo-elastic and numerical techniques, they found the
distribution of stress within a cross section of a loaded grain. This technique can be a useful method for theoretical evaluation of grain damage.

**Carbon dioxide production method** Steele (1967) and Kalbasi et al. (1979) studied the effect of mechanical damage on deterioration rate of shelled corn. Their tests were based on the following respiration equation for a typical carbohydrate:

\[ C_6H_{12} + 6O_2 + 6CO_2 + 6H_2O + 673 \text{ cal.} \]

The increase in the rate of deterioration caused by mechanical damage was estimated by measurement of corresponding increases in carbon dioxide production of the grain.

**Economic Aspects of Damage**

Damaged kernels are more susceptible to molds and fungi invasion which degrade oil, and may result in development of mycotoxins. Heat damage due to high temperature drying sometimes makes it difficult to separate protein from starch. If heat and mold damage the germ, oxidation and the formation of free fatty acids lower the yields and quality of oil extracted. Also, damaged corn is more susceptible to insect infestation (Liebenow, 1972). Therefore, at the elevator there are some penalty discounts imposed on damaged corn. In grain marketing, damaged kernels refer to kernels that are heat damaged, sprouted, frosted, badly ground damaged, badly weather damaged, moldy, diseased, or otherwise materially damaged (Kaminski, 1968). The penalty discount rates
vary from time to time and among the elevators.

**Test weight discount**

The weight of one bushel of corn or 1.245 ft$^3$ as determined on a test weight apparatus is called test weight. Mature kernels will show a higher test weight per bushel than will smaller shriveled kernels. Moisture content has an affect on test weight (Uhrig, 1968).

Test weight discount was about 2 cents per pound per bushel for corn under 54 pounds per bushel in central Iowa in Spring 1981 (Hurburgh, 1981).

**Broken corn and foreign material discounts**

Broken corn is fines which pass through a 4.76 mm round hole sieve. Any material other than corn that does not pass through 4.76 mm round hole sieve is foreign material. The percentage of BCFM is computed from the weight of the fines and foreign material removed from the weight of the original sample. The discount for BCFM is about 2 cents per bushel per percent BCFM over 3% (Hurburgh, 1981).

**Damaged kernel discounts**

Damaged kernels consist of total damage and heat damaged kernels. Total damage discounts are assessed on all grain containing over 5% damage. The discount for total damage is about 1% shrink per percent damage over 5% (Hurburgh, 1981). The market difference will usually apply for grain containing over 15% damage. The market difference means the discount will depend specifically on the factors causing the lower
grades and how much the seller can get in an attempt to merchandise the damaged grain or the buyer can use of the damaged grain. Heat damage over 0.2% will usually be subjected to the market difference (Uhrig, 1968).

The damage of corn comes from many causes, the major problem being brittle kernels. Bailey (1968) proposed the solutions to reduce cracked kernels by:

1. Harvesting at 23% moisture or less.
2. Limiting kernel temperature in drying to 60°C.
3. Not drying below 14.5% moisture.
4. Not heating grain over 1.5 hours.
5. Avoiding batch drying with continuous heated air without turning.
OBJECTIVES

The objectives of this research are:

(1) To determine the breakage susceptibility of blended wet and dry shelled corn.

(2) To examine the moisture content of wet and dry corn fractions after blending and storage.

(3) To determine a blending ratio to minimize damage.

(4) To evaluate economic aspects of blending.
Experimental Design

This experiment was designed to determine the damage susceptibility and moisture content of wet, dry and blended portions of blended corn after a storage period.

The experiment included the following treatments: (1) one control with three replications; and (2) four levels of dry corn (8, 9, 11% and 8.9% moisture desiccant) and 2 levels of theoretical moisture content of blend (15.5% and 20%). The moisture contents of dry corn represented limits of desiccant production, under 8% moisture was not feasible, and over 11% moisture took too much desiccant. The 15.5% theoretical moisture content of the blend was selected as the same moisture required for No. 2 corn in the market. The 20% moisture content of blend was chosen as suitable for low temperature drying at low cost (Bern et al., 1980).

Each level of blend was obtained by blending appropriate weights of wet corn from the field at 24.4% moisture content with dry corn. The experimental unit consisted of a level of dry corn at a level of blend. Each unit had 3 replications for a total of 24 replications. Each replication was confounded to determine the effect of wet only, dry only, and blended corn, giving a total of 72 samples. The layout of the experiment is shown in Fig. 13.

Therefore, there were 75 readings for moisture content determination and 75 readings for breakage tester tests. The flow chart of the
Fig. 13. Layout of the experiment
experimental design is shown in Fig. 14.

Grain

Yellow dent corn (Pioneer 3780) was picked by hand at the Agronomy-Agricultural Engineering Research Center located west of Ames, Iowa, in the fall of 1980. The moisture content of corn at the harvesting time was 25%. It was shelled with an International Harvester electric motor-driven one hole corn sheller. The shelled corn was cleaned with a Carter Dockage Tester with the sieve size 6.35 mm. The sound kernels which passed through 6.35 mm round hole sieve of the Carter Dockage Tester were picked by hand and used as test grain. The sound kernels were kernels without any broken parts. About 20 kg of corn were used in the experiments.

Moisture Determination

All the moisture contents of corn in the experiment were determined by the air-oven method as described by ASAE Standard S352 (Agric. Engr. Yearbook, 1981). The procedure is as follows:

(1) Place a minimum of 15 g of a representative portion of the unground sample in each of three tared moisture dishes.

(2) Weigh the covered dishes and contents.

(3) Subtract the weight of each dish from the total weight and record the weight of the portion.

(4) Uncover the dishes and place them with their covers in the oven.

(5) The oven temperature is 103°C, and the heating period is 72 hours.
**Fig. 14. Flow chart of experimental design**
(6) After 72 hours, cover the dishes and weigh the dishes when they reach room temperature (the accuracy of weighing is ±0.001 g).
(7) Calculate the percentage of moisture by dividing the loss in weight due to heating by the weight of the original sample and multiply by 100.

Wet Portion

The wet portions were prepared as follows:

(1) Use 1 kg wet corn at 24.4%.
(2) Immerse the grain sample for 5 minutes in 1000 mL of distilled water + 2 g Fast green FCF dye (Fig. 15).
(3) Drain the dye and rinse the corn under running tap water for one minute.
(4) Pour the grain on the strainer and dry down to get 1 kg of wet corn again. This corn then retains the 24.4% moisture content.

The weight of wet corn for preparing the wet portion was 8 kg. The dye colored the tips of corn blue and allowed identification of the wet portions of blends.

Dry Portion

An experimental drier was used to dry the yellow dent corn to the required moisture contents (Fig. 16). It had two 0.12-hp single phase electric motors and two blowers with 10 cm radial blade fan which delivered air at room temperature at the aeration rate of about 4 L/s.kg
Fig. 15. Dyeing corn for preparing wet portion corn

Fig. 16. Laboratory natural air dryer used for drying corn until desired moisture content was realized
of dry matter through a plenum chamber. Above the perforated floor, there were 30 wooden boxes with mesh bottoms, into which the corn samples were placed for drying.

The moisture contents of the dry samples were obtained by the following methods:

1. Calculate the mass of water for the required moisture content of the sample.
2. Calculate the mass of water to be removed in order to obtain the desired moisture content.

Three 1-kg corn lots of wet corn were dried to 12.8±0.2% and were used as control samples.

Three 3-kg lots of wet corn were dried to 11%, 9%, and 8%, respectively, and were used as dry portions.

Desiccant Corn

Desiccant corn was collected from the desiccant bin located at Iowa State University Woodruff Farm, southwest of Ames. This desiccant corn had been dried over summer 1980 with heat from a solar collector. Its moisture content was 8.9%. The sound desiccant kernels were picked by hand and the total weight of desiccant was 3 kg.

Blending of Grain

Wet and dry portions were blended to obtain the final theoretical moisture contents of 15.5% and 20%. The required weight of each portion was calculated by using the equation:

\[ M_F(x + y) = M_d(y) + M_w(x) \]
where:

\[ M_F = \text{final theoretical moisture content of blended portion, wet basis, decimal;} \]
\[ x = \text{weight of wet portion, g;} \]
\[ y = \text{weight of dry portion, g;} \]
\[ M_d = \text{moisture content of dry portion, wet basis, decimal;} \]
\[ M_w = \text{moisture content of wet portion, wet basis, decimal.} \]

The weights of wet and dry portions were determined depending on the type of experiment to be carried out after the blending and the volume of the storage jar. For this experiment, each portion needed 15 g for moisture measurement and 180 g for breakage tests. Each sample had to have at least 195 g of wet or dry portion. For 15.5% theoretical moisture of blend, the weight of dry portions was chosen arbitrarily from 300 to 500 g, and the wet portions would be from 219.9 g to 259.5 g. The total sample size ranged from 519.1 g to 609.5 g. For the 20% theoretical moisture blend, the weight of all the dry portions was 250 g, and the wet portions were from 511.4 g to 681.8 g. The total sample size ranged from 761.4 g to 931.8 g. The weights of samples are listed in Tables 7 and 8.

Table 7. Weight of samples (15.5% theoretical moisture blend)

<table>
<thead>
<tr>
<th>Dry portion at % moisture</th>
<th>8%</th>
<th>9%</th>
<th>11%</th>
<th>Desiccant 8.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of dry portion (g)</td>
<td>300.0</td>
<td>300.0</td>
<td>500.0</td>
<td>350.0</td>
</tr>
<tr>
<td>Weight of wet portion (g)</td>
<td>252.8</td>
<td>219.1</td>
<td>252.8</td>
<td>259.5</td>
</tr>
<tr>
<td>Total weight (g)</td>
<td>552.8</td>
<td>519.1</td>
<td>752.8</td>
<td>609.5</td>
</tr>
<tr>
<td>Ratio wet portion/dry portion</td>
<td>0.84</td>
<td>0.73</td>
<td>0.51</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Table 8. Weight of samples (20% theoretical moisture blend)

<table>
<thead>
<tr>
<th></th>
<th>8%</th>
<th>9%</th>
<th>11%</th>
<th>Desiccant 8.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of dry portion (g)</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
</tr>
<tr>
<td>Weight of wet portion (g)</td>
<td>681.8</td>
<td>625.0</td>
<td>511.4</td>
<td>630.7</td>
</tr>
<tr>
<td>Total weight (g)</td>
<td>931.8</td>
<td>875.0</td>
<td>761.4</td>
<td>880.7</td>
</tr>
<tr>
<td>Ratio wet portion/dry portion</td>
<td>2.70</td>
<td>2.50</td>
<td>2.04</td>
<td>2.52</td>
</tr>
</tbody>
</table>

The dry and wet portions were blended using a Boerner divider. Four lots of 3 samples each of wet and dry portion were blended to a theoretical moisture content of 15.5% and another 4 lots of samples of wet and dry portion were blended to 20% moisture. These samples were held in 2-qt jars (Fig. 17) and stored at 20°C room temperature one day and then three days at 2°C. During the storage time, samples were disturbed three times per day by turning upside down five times.

After four days, samples were separated into dry, wet and blended portions by hand. These portions were kept in separate sealed jars and left three days in the cold room while awaiting moisture determination.

When the moisture of separated portions was known, they were conditioned to 12.8±0.2% moisture by natural air at 20°C and held at 2°C for two days to equalize moisture before breakage testing.

**Stein Breakage Tester**

A Stein CK-2M breakage tester was used in this experiment (Fig. 18). It had a 1/3 hp electric motor and an impeller speed of 1725 rpm.
Fig. 17. Samples of corn were held in 2-qt jars

Fig. 18. Stein breakage tester Model CK-2M
with no load. The inside cup dimensions were 8.9 cm high, 9.2 cm in
diameter. The cup volume was 593.2 cm$^3$. The clearance between the
impeller and the bottom of the cup was 0.51 mm plus or minus 0.13 mm
(Miller et al., 1980).

The procedure for conducting a Stein breakage test on corn sample
was recommended by NC-151 collaborative study (Miller et al., 1980).
The outline of the procedure is as follows:

1. Remove all nongrain material by hand from the sample.
2. Use the U.S.D.A. air oven procedure to determine moisture
   content.
3. The moisture content of the sample is to be 12.8±0.2%.
4. If the sample is not at the above range, it needs to be con-
   ditioned to that range. After that, leave the sample in a
cold room for two days to equalize moisture before breakage
testing (sample size was 100±1 g; sample was placed in Stein
tester for four minutes).
5. After testing, screen grain by use of 4.76 mm round hole
   sieve.
6. Weigh the fines passing through the sieve and calculate the
   percent breakage:

   \[
   \text{Percent breakage} = \frac{\text{weight of fines}}{\text{weight of sample}} \times 100
   \]
RESULTS AND DISCUSSION

Moisture Content after Storage

Tables 9 and 10 and Figs. 19 and 20 show the moisture content of wet and dry portions of corn of the same variety after being stored for a day at 20°C and then 3 days at 2°C. The moisture content of the two portions never reached the theoretical moisture content of the blend. The difference in moisture contents between the wet and dry portions ranged from 1.52 to 2.61 points for the 15.5% theoretical moisture blend and from 1.07 to 1.52 points for the 20% theoretical moisture blend.

Standard deviations of the wet and dry portion moisture contents after storage from the portion's average moisture content for 15.5% and 20% theoretical moisture blends ranged from 0.03 to 0.14 point and from 0.01 to 0.32 point, respectively.

Moisture content of blend portions taken randomly from the samples ranged from 15.37 to 15.68 for the 15.5% theoretical moisture blend and from 19.96 to 20.10 for the 20% theoretical moisture blend. These blended portion samples were conditioned for Stein breakage tests.

Table 11 shows the moisture content of desiccant and wet portion of corn after being stored for a day at 20°C and 3 days at 2°C. The average difference in moisture content between desiccant and wet portions was 2.51 points and 1.52 points for 15.5% and 20% theoretical moisture of blend, respectively. These differences were higher than with those in the same variety corn.

The difference in moisture contents between wet and dry portions may
Table 9. Moisture content of dry and wet portions after being stored one day at 20°C and then three days at 2°C (15.5% theoretical moisture content of blend)

<table>
<thead>
<tr>
<th>Dry portion</th>
<th>Wet portion</th>
<th>Moisture content after storage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>24.4</td>
<td>14.65 16.63 15.55</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>14.77 16.64 15.47</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>14.66 16.59 15.25</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>14.69 16.52 15.42</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.07</td>
<td>0.03 0.15</td>
</tr>
</tbody>
</table>

| 9           | 24.4        | 14.44 17.14 15.65                |
| 9           | 24.4        | 14.71 17.19 15.78                |
| 9           | 24.4        | 14.64 17.24 15.61                |
| Average     |             | 14.58 17.19 15.68                |
| Standard deviation | 0.14 | 0.05 0.09                   |

| 11          | 24.4        | 15.07 16.61 15.34                |
| 11          | 24.4        | 14.98 16.51 15.40                |
| 11          | 24.4        | 15.06 16.57 15.36                |
| Average     |             | 15.04 16.56 15.37                |
| Standard deviation | 0.05 | 0.05 0.03                   |
Table 10. Moisture content of dry and wet portion after being stored one day at 20°C and then three days at 2°C (20% theoretical moisture content of blend)

<table>
<thead>
<tr>
<th>Original moisture content, %</th>
<th>Moisture content after storage, %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry portion</td>
<td>Wet portion</td>
<td>Dry portion</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>19.37</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>19.36</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>19.37</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>19.37</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>9</td>
<td>24.4</td>
<td>18.63</td>
</tr>
<tr>
<td>9</td>
<td>24.4</td>
<td>19.14</td>
</tr>
<tr>
<td>9</td>
<td>24.4</td>
<td>19.23</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>19.00</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td>11</td>
<td>24.4</td>
<td>19.39</td>
</tr>
<tr>
<td>11</td>
<td>24.4</td>
<td>19.40</td>
</tr>
<tr>
<td>11</td>
<td>24.4</td>
<td>19.40</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>19.40</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>0.01</td>
</tr>
</tbody>
</table>
Fig. 19. Moisture content of portions after storage versus original moisture content of dry portion (15.5% theoretical moisture content of blend)
Fig. 20. Moisture content of portions after storage versus original moisture content of dry portion (20% theoretical moisture content of blend)
Table 11. Moisture content of desiccant and wet portions after being stored one day at 20°C and then three days at 2°C (15.5% and 20% theoretical moisture content of blend)

<table>
<thead>
<tr>
<th>Theoretical moisture content of blend, %</th>
<th>Original moisture content, %</th>
<th>Moisture content after storage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Desiccant</td>
<td>Wet portion</td>
</tr>
<tr>
<td></td>
<td>Moisture content, %</td>
<td>Moisture content after storage, %</td>
</tr>
<tr>
<td>15.5%</td>
<td>8.9</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>8.9</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
be explained as the result of equilibrium moisture content. The dry portion is represented by adsorption curve and the wet portion is represented by desorption curve. The difference between two curves is hysteresis effect (Chung and Pfost, 1967). The hysteresis effect is based on the effect of capillary condensation, multi-molecular adsorption and capillary condensation giving the adsorption curve or dry portion. The capillary condensation alone accounts for the desorption curve or wet portion (Allen, 1960).

The prediction line of moisture content after storage for dry, wet and blended portions has this form:

$$Y_{D,W,B} = a + bX$$

where:

- \(Y_D, Y_W, Y_B\) = moisture content of dry, wet and blended portions after storage, wet basis, percent;
- \(a\) = intercept;
- \(b\) = slope;
- \(X\) = moisture content of dry portion in a blend.

For 15.5% theoretical moisture of blend, the following equations are derived for moisture content after storage for dry, wet and blended portions:

$$Y_D = 13.57 + 0.13 X$$
$$Y_W = 17.36 - 0.06 X$$
$$Y_B = 15.85 - 0.04 X$$
The above equations are based on a moisture content of the wet portion at 24.4% and moisture content of dry portions in the range from 8 to 11%. The plots of lines are in Fig. 21.

For 20% theoretical moisture of blend, the prediction equations for moisture content after storage of dry, wet and blended portions are as follows:

\[ Y_D = 18.91 + 0.04 X \]
\[ Y_W = 21.16 - 0.06 X \]
\[ Y_B = 20.06 - 0.01 X \]

The above equations are based on moisture content of wet portion at 24.4% and moisture content of dry portion in the range from 8 to 11%. The plots of lines are in Fig. 22.

Susceptibility to Breakage

Tables 12 and 13 and Figs. 23, 24, and 25 show breakage of dry, wet and blended portions. Average breakage for the control lot was 6.13%.

The breakages of blends of wet portions at 24.4% and dry portions at 8, 9 and 11% moisture at 15.5% theoretical moisture of blend were 9.43%, 8.10%, and 6.87%, respectively. This indicates that the lower the moisture content of the dry portion, the higher was the susceptibility to breakage. The breakage of a blend of wet portion at 24.4% and desiccant at 8.9% moisture was 10.60%. The blend of wet corn and desiccant exhibited greater breakage. This desiccant may have been damaged because of machine harvest and additional handling. Another possible reason may
Fig. 21. Prediction lines of moisture content of portions after storage versus original moisture content of dry portion (15.5% theoretical moisture content of blend)
Fig. 22. Prediction lines of moisture content of portions after storage versus original moisture content of dry portion (20% theoretical moisture content of blend)
Table 12. Breakage susceptibility of corn blended to 15.5% theoretical moisture (control breakage = 6.13%)

<table>
<thead>
<tr>
<th>Original moisture content of dry portion</th>
<th>8%</th>
<th>9%</th>
<th>11%</th>
<th>Desiccant 8.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakage of dry portion %</td>
<td>9.1</td>
<td>9.8</td>
<td>7.5</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
<td>9.6</td>
<td>7.3</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td>9.9</td>
<td>7.4</td>
<td>18.4</td>
</tr>
<tr>
<td>Average</td>
<td>10.17</td>
<td>9.77</td>
<td>7.40</td>
<td>19.93</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>0.97</td>
<td>0.15</td>
<td>0.10</td>
<td>1.39</td>
</tr>
<tr>
<td>Breakage of wet portion %</td>
<td>5.9</td>
<td>6.1</td>
<td>6.2</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>5.9</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>6.9</td>
<td>6.3</td>
<td>6.3</td>
<td>6.7</td>
</tr>
<tr>
<td>Average</td>
<td>6.40</td>
<td>6.10</td>
<td>6.50</td>
<td>7.87</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>0.50</td>
<td>0.20</td>
<td>0.44</td>
<td>1.10</td>
</tr>
<tr>
<td>Breakage of blend %</td>
<td>8.0</td>
<td>8.4</td>
<td>7.2</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td>8.0</td>
<td>6.9</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>9.2</td>
<td>7.9</td>
<td>6.5</td>
<td>11.3</td>
</tr>
<tr>
<td>Average</td>
<td>9.43</td>
<td>8.10</td>
<td>6.87</td>
<td>10.60</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>1.56</td>
<td>0.26</td>
<td>0.18</td>
<td>0.44</td>
</tr>
<tr>
<td>Difference between breakage of blend and control breakage, %</td>
<td>3.30</td>
<td>1.97</td>
<td>0.74</td>
<td>4.47</td>
</tr>
</tbody>
</table>
Table 13. Breakage of susceptibility of corn blended to 20% theoretical moisture (control breakage = 6.13%)

<table>
<thead>
<tr>
<th>Original moisture content of dry portion</th>
<th>8%</th>
<th>9%</th>
<th>11%</th>
<th>Desiccant 8.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakage of dry portion %</td>
<td>32.3</td>
<td>24.8</td>
<td>15.3</td>
<td>42.7</td>
</tr>
<tr>
<td></td>
<td>28.0</td>
<td>25.2</td>
<td>11.9</td>
<td>45.2</td>
</tr>
<tr>
<td></td>
<td>28.0</td>
<td>21.4</td>
<td>18.9</td>
<td>42.1</td>
</tr>
<tr>
<td>Average</td>
<td>29.43</td>
<td>23.8</td>
<td>15.36</td>
<td>43.33</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>2.48</td>
<td>2.09</td>
<td>3.50</td>
<td>1.64</td>
</tr>
<tr>
<td>Breakage of wet portion %</td>
<td>5.2</td>
<td>5.8</td>
<td>6.3</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>5.9</td>
<td>6.5</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>6.1</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Average</td>
<td>5.23</td>
<td>5.93</td>
<td>6.30</td>
<td>7.17</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>0.06</td>
<td>0.15</td>
<td>0.20</td>
<td>1.26</td>
</tr>
<tr>
<td>Breakage of blend %</td>
<td>14.2</td>
<td>8.3</td>
<td>7.5</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>13.4</td>
<td>9.3</td>
<td>8.3</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>13.0</td>
<td>10.2</td>
<td>7.2</td>
<td>18.0</td>
</tr>
<tr>
<td>Average</td>
<td>13.53</td>
<td>9.27</td>
<td>7.67</td>
<td>16.73</td>
</tr>
<tr>
<td>Standard deviation, points</td>
<td>0.61</td>
<td>0.95</td>
<td>0.57</td>
<td>1.25</td>
</tr>
<tr>
<td>Difference between breakage of blend and control breakage, %</td>
<td>7.40</td>
<td>3.14</td>
<td>1.54</td>
<td>10.60</td>
</tr>
</tbody>
</table>
Fig. 23. Kernel breakage as affected by moisture content of dry portion (15.5% theoretical moisture blend)
Fig. 24. Kernel breakage as affected by moisture content of dry portion (20% theoretical moisture blend)
Fig. 25. Breakage vs. theoretical moisture content of blend
be a yearly carry over of desiccant corn because of intentional incomplete unloading of the bin.

Standard deviation of the blending portion for 15.5% theoretical moisture ranged from 0.18 to 1.56 points. The breakage of a blend of wet portion at 24.4% and dry portion at 8, 9 and 11% moisture at 20% theoretical moisture of blend was 13.53%, 9.27%, and 7.67%, respectively. This indicates that the lower the moisture content of the dry portion, the greater was the susceptibility. The breakage of a blend of wet portion at 24.4% and desiccant at 8.9% moisture was 16.73%.

Standard deviation of blended portion for 20% theoretical moisture ranged from 0.57 to 1.25 points.

The difference between breakage of blend at 15.5% moisture and control breakage ranged from 0.74% to 4.47%, while at 20% moisture of blend, the difference between breakage of blend and control breakage ranged from 1.54% to 10.60%. Therefore, blending wet and dry corn at 15.5% theoretical moisture of blend results in less breakage due to blending than at 20% theoretical moisture of blend (Fig. 26). This may be explained by noting that the cycle of corn from 24.4% to a lower moisture content (11% or less) and rewetting it to 20% is longer than rewetting it to 15.5%.

For the 20% theoretical moisture of blend, breakage of dry portions ranged from 15.36 to 43.33%. The breakage of wet portions ranged from 5.23% to 7.17%, but the breakage of blended portions ranged from 7.67 to 16.73%. These were not proportional with the ratio of blending of wet and dry portions. This may be explained by the fact that the wet portion acts as a "cushion" in the blended portions and thus is effective
Fig. 26. Kernel breakage as affected by moisture content of dry portion (15.5% and 20% theoretical moisture blend)
in preventing breakage of the dry portion during the breakage tests.

The prediction line of breakage of dry, wet and blended portions is of this form:

\[ Y_{D,W,B} = A + BX \]

where

- \( Y_D, Y_W, Y_B \) = breakage of dry, wet, and blended portions, respectively, percent;
- \( A \) = intercept;
- \( B \) = slope;
- \( X \) = moisture content of dry portion, wet basis, percent.

For 15.5% theoretical moisture of blend, the following equations are derived for breakage of dry, wet and blended portions:

- \( Y_D = 18.07 - 0.96 X \)
- \( Y_W = 5.80 + 0.06 X \)
- \( Y_B = 15.80 - 0.82 X \)

The above equations are based on moisture content of wet portion at 24.4% and dry portions ranging from 8 to 11% moisture. The plots of lines are in Fig. 27.

For 20% theoretical moisture of blend, the prediction equations for breakage of dry, wet and blended portions are as follows:

- \( Y_D = 66.00 - 4.62 X \)
- \( Y_W = 2.73 + 0.33 X \)
- \( Y_B = 26.87 - 1.79 X \)
Fig. 27. Prediction lines of kernel breakage as affected by moisture content of dry portion (15.5% theoretical moisture of blend).
The above equations are based on moisture content of wet portions at 24.4% and dry portions ranging from 8 to 11% moisture. The plots of lines are in Fig. 28.

Selecting the Blending Ratio

The breakage susceptibility of blended corn changed with the ratio of blending wet and dry corn and with the level of theoretical moisture of blend. A statistical analysis was performed comparing breakage at different dry portion moisture contents within the same level of theoretical moisture of blend at the same level moisture of dry portion (Steel and Torrie, 1980).

For blending wet corn and dry corn

The analysis of variance procedure for breakage due to blending wet and dry corn in the blended portions is shown in Table 14.

Table 14. Analysis of variance for breakage of blended portions due to blending

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>5</td>
<td>83.4711</td>
<td>16.6942</td>
</tr>
<tr>
<td>Error</td>
<td>12</td>
<td>8.4733</td>
<td>0.7061</td>
</tr>
<tr>
<td>Corrected total</td>
<td>17</td>
<td>91.9444</td>
<td></td>
</tr>
</tbody>
</table>

The least significant difference (LSD) at the 95% confidence level (Little and Hills, 1978) is:

\[ \text{LSD} = t_{.05} \sqrt{\frac{2 \cdot \text{EMS}}{n}} \]
Fig. 28. Prediction lines of kernel breakage as affected by moisture content of dry portion (20% theoretical moisture of blend)

\[ Y_D = 66.00 - 4.62X \]

\[ Y_B = 26.87 - 1.79X \]

\[ Y_W = 2.73 + 0.33X \]
where:

\[ \text{LSD} = \text{Fisher's least significant test}; \]
\[ t_{.05} = t \text{ statistic at 95\% confidence level and degrees of freedom of error}; \]
\[ n = \text{replication}; \]
\[ t_{.05} \text{ (at 12 degrees of freedom)} = 2.179. \]

So,

\[ \text{LSD} = 2.179 \sqrt{\frac{2(0.706)}{3}} \]
\[ \text{LSD} = 1.495 \]

If the breakage difference between wet corn and dry corn at 8 and 9\%, 8 and 11\%, and 9 and 11\% is smaller than the LSD value, we conclude that the breakage difference is not significantly different. If they are larger than the LSD value, we conclude that the breakage difference is significantly different.

The breakage difference between wet and dry portions in the blended portions at the same level of theoretical moisture of blend and at different levels of theoretical moisture of blend are summarized in Table 15.

From the values in Table 15 and the value of LSD, the analysis of variance indicated that:

1. The differences in breakage between 8 and 9\%, 9 and 11\% moisture of dry portion of 15.5\% theoretical moisture blend are not significantly different, but the difference between 8 and 11\% is significantly different.
Table 15. Breakage of blended portion

<table>
<thead>
<tr>
<th>Theoretical moisture of blend</th>
<th>8%</th>
<th>9%</th>
<th>11%</th>
<th>Difference between 8 and 9%</th>
<th>Difference between 9 and 11%</th>
<th>Difference between 8 and 11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5%</td>
<td>9.433</td>
<td>8.100</td>
<td>6.867</td>
<td>1.333</td>
<td>1.233</td>
<td>2.566*</td>
</tr>
<tr>
<td>20%</td>
<td>13.533</td>
<td>9.267</td>
<td>7.667</td>
<td>4.266*</td>
<td>1.600*</td>
<td>5.866*</td>
</tr>
<tr>
<td>Difference between 15.5% and 20%</td>
<td>4.100*</td>
<td>1.167</td>
<td>0.800</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Significant difference at 95% confidence level.

(2) The differences in breakage between 8 and 9%, 9 and 11%, and 8 and 11% moisture content of dry portion at 20% theoretical moisture of blend are significantly different at the 95% confidence level.

(3) The differences in breakage between two levels of theoretical moisture of blend at 9 and 11% moisture of dry portion are not significantly different but at 8% moisture level of dry portion they are significantly different at the 95% confidence level.

For blending wet corn and desiccant

The analysis of variance for breakage due to blending wet corn and desiccant (8.9% corn from desiccant bin) is shown in Table 16.

Fisher's least significant difference at 95% confidence level

\[
LSD = 2.776 \sqrt{\frac{2(0.9967)}{3}}
\]

\[
LSD = 2.263
\]
Table 16. Analysis of variance for breakage due to blending wet corn and desiccant at two levels of theoretical moisture of blend

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1</td>
<td>56.4267</td>
<td>56.4267</td>
</tr>
<tr>
<td>Error</td>
<td>4</td>
<td>3.9867</td>
<td>0.9967</td>
</tr>
<tr>
<td>Corrected total</td>
<td>5</td>
<td>60.4133</td>
<td></td>
</tr>
</tbody>
</table>

The breakage of blended wet corn and desiccant at 15.5% and 20% moisture of blend was 10.6% and 16.73%, respectively. The difference between them was 6.133%. It is larger than LSD value. Therefore, they are significantly different at the 95% confidence level.

From the above analysis, we can draw the following conclusions:

(1) Blends of wet and dry corn at 9 and 11% moisture of dry portion to 15.5% or 20% theoretical moisture of blend are not significantly different in breakage.

(2) For 15.5% theoretical moisture of blend, blending wet and dry corn at 11% moisture will have the least breakage. But at lower dry portion moisture contents, we have a better ratio of blending, that means with the same amount of dry corn, we can blend with a larger amount of wet corn. But the lower moisture content of the dry corn also means that the drying time must be longer and more energy is spent for drying.
Economic Aspects of Blending

In the grain trade, corn which has a BCFM level less than 3% is not subjected to any discount. Unpublished results from three years of tests at Iowa State University indicate that the BCFM level of low temperature drying is about 1% (G. L. Kline, Agric. Engineer, USDA, Agric. Engr. Dept., Iowa State Univ., 1981, personal communication). This BCFM level included damage from the harvest to the drying bin. What percent of breakage will be added between the drying bin to the final destination is not known exactly. We can predict the breakage which will occur after blending from the farm to the elevator if we assume the handling system and corn used by Stephens and Foster (1976) would be representative. Stephens and Foster (1976) used corn with the moisture content range from 10.3 to 13.5% for both the 4-minute Stein test and for sieving to measure broken corn due to handling. For this study, we will consider the ratio between Stein test breakage and actual breakage. From Table 5 in the literature review, the ratio between Stein tester breakage and actual breakage of corn due to handling ranged from 4.85 to 8.05 with the mean ratio 6.30 to 1. This means that for the same sample of corn after moving through a handling system, the broken corn measured by a Stein breakage tester is 6.30 times more than broken corn measured by the sieving method.

From Table 8, the difference in breakage between breakage of blend and control breakage at 8, 9, 11 and 8.9% moisture desiccant of 15.5% moisture of blend are 3.30, 1.97, 0.74 and 4.47%, respectively. The actual breakage difference between blended and control based on a ratio of
6.30 to 1 will be 0.52, 0.31, 0.12 and 0.71%. The actual BCFM in this system can be assumed to be the sum of normal BCFM of the conventional low temperature system and the 0.52, 0.31, 0.12 and 0.71% due to handling. This predicted total of 1.52, 1.31, 1.12 and 1.71% BCFM for 8, 9, 11 and 8.9% moisture desiccant, respectively, will not result in any discount at the time of sale by the producer.

From Table 9, the differences in breakage between breakage of blend and control breakage at 8, 9, 11 and 8.9% moisture desiccant of 20% moisture blend are 7.40, 3.14, 1.54 and 10.60%, respectively. The actual breakage difference between blended and control based on ratio 6.30 to 1 will be 1.17, 0.50, 0.24 and 1.68%. The actual BCFM in this system will be the sum of normal BCFM of the conventional temperature system and the 1.17, 0.50, 0.24 and 1.68% due to handling. This predicted total of 2.17, 1.50, 1.24 and 2.68% BCFM for 8, 9, 11 and 8.9% moisture desiccant, respectively, is not likely to result in any discount at the time of sale by the producer.
SUMMARY

Wet corn from the field, dried in the laboratory by natural air to 8, 9, and 11%, and desiccant corn at 8.9% from the solar grain drying bin were used as dry portions. These dry portions were blended with wet corn at 24.4% moisture content to produce blends of 15.5 and 20% theoretical moisture. After storage for 4 days, the samples were separated into the original portions.

The moisture content difference between the dry and wet portions of blended corn ranged from 1.51 to 2.75% for 15.5% theoretical moisture blend and from 1.02 to 1.54% for 20% theoretical moisture blend. The moisture content difference between the wet portion and the dry portion at 11% moisture had the lowest difference. The highest difference between wet portion and dry portion was at 9% moisture for both 15.5% and 20% theoretical moisture blend. The moisture content difference between wet and dry corn at 20% theoretical moisture of blend was lower than at 15.5% theoretical moisture of blend.

The breakage susceptibility for a blend of wet and dry corn ranged from 6.87% to 10.60% for 15.5% theoretical moisture blend and from 7.67% to 16.73% for 20% theoretical moisture blend. The breakage of blended corn increased with the decreasing moisture content of dry portion (11, 9 and 8% moisture) for both 15.5% and 20% theoretical moisture of blend. The breakage of a blend of wet and desiccant corn had higher breakage for both the 15.5 and 20% theoretical moisture blend.

The blending of wet and dry corn increases breakage susceptibility.
But those breakage values are not likely to result in a discount at the time of sale.
CONCLUSIONS

The following conclusions can be drawn from this study.

(1) The moisture content of wet and dry portions in the blend do not equalize in 4 days in storage.

(2) Blending wet and dry corn to 15.5% and 20% theoretical moisture of blend will increase the breakage susceptibility of corn. The breakage susceptibility increases with a decrease in moisture content of dry portions and this breakage susceptibility is higher at the 20% theoretical moisture of blend than at 15.5% theoretical moisture of blend.

(3) Based on the ratio of Stein breakage tester breakage and the actual breakage which have been reported by previous studies, the breakage susceptibility of blended wet and desiccant corn is not likely to result in a discount at the time of sale.
SUGGESTIONS FOR FURTHER STUDY

(1) Prediction of breakage susceptibility due to handling in this study was based on the ratio of predicted breakage with the Stein breakage tester and actual breakage which has been done by previous researchers. It is necessary to determine this ratio with the same variety of corn and with the same procedure for Stein breakage tester.

(2) The breakage susceptibility of blended corn may change with different varieties, methods of harvesting, handling and drying. Therefore, further research based on the above variables is needed.
REFERENCES

Agricultural Engineers Yearbook. 1981. Published by the American Society of Agricultural Engineers, St. Joseph, Michigan.


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