# Moisture Adsorption Related to the Tensile Strength of Rice[1]

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## ABSTRACT

Investigations were conducted on the tensile strength of individual rice kernels at moisture-equilibrated conditions and also at certain intervals after the grains were exposed to a moisture-adsorbing environment. Retardation times (time required to obtain initial fissuring when kernels equilibrated at 74°F. and 44% relative humidity [r.h.] were suddenly exposed to 86 or 100% r.h. atmospheres at the same temperature) were dependent on variety, form of rice, and the amount of change in r.h. The rate of moisture adsorption depended on the form of rice and the r.h. change in the environment. Variations in tensile strength were large between individual kernels, but were small between average groups of like kernels. Within retardation time, the tensile strength was related to the time after exposure. Quadratic equations gave the best fit to these data. Hypothetical two-dimensional stress analyses for longitudinal sections of kernels were developed to give theoretical explanations of the observed behavior.

Rice (*Oryza sativa* L.) has been and continues to be the most important food in the world. About one-fourth of the world's population depends on rice as a major staple food (1). The ultimate goal of the rice industry is to produce a maximum amount of whole-grain rice from each hundredweight of product milled. Recent research indicates that much breakage in rice may occur because the rice kernels have previously been weakened by stress cracks (fissures) caused by rapid moisture adsorption or desorption due to ordinary changes in weather during harvesting, handling, and processing.

The rice industry and its design engineers need to know the engineering properties of rice for accurate analysis, design, and operation of harvesting, processing, transportation, and storage of rough-, brown-, and milled-rice systems. The objectives (2) of this research were to determine: a) the retardation times required to obtain initial fissuring responses for brown and polished rice kernels under given environmental conditions, b) the tensile strength of brown and polished rice kernels, c) the change in tensile strength of brown and polished rice kernels after the grains had adsorbed moisture from a higher-relative-humidity environment, and d) to develop mathematical expressions for rice which relate tensile strength to exposure time.

## REVIEW OF LITERATURE

The first observation of rice grains cracking due to moisture adsorption was reported by Kondo and Okamura (3) in 1929. A similar independent observation was made by Stahel (4) in 1932. In 1961 Desikachar and Subrahmanyan (5) observed the formation of cracks in rice grains due to wetting and determined their

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effects on the cooking characteristics of the grain. In 1964, Kunze (6) observed the development of fissures when grains originally at storage moisture were exposed to a more humid environment. Later Stermer (7) conducted research on milled rice and developed a relationship between stress-crack damage and the magnitude of change in the equilibrium moisture content. Kunze and Hall (8) developed a hypothesis which states that moisture adsorbed by the external cells causes them to expand and produce compressive stresses in the surface layers of the kernels which themselves act as free bodies. As the expansion continues, the compressive stresses are intensified and opposite tensile stresses are produced at the center along the longitudinal axis. As a result, fissures develop across the longitudinal axis when the compressive forces parallel to the longitudinal axis exceed the tensile strength of the inner portions of the grain. Conversely, Earle and Ceaglske (9) investigated factors causing the checking of macaroni and showed that the reduction of the moisture gradient towards the end of drying set up tensile stresses in the outer surface which were sufficient to cause checking. Grosh and Milner (10), in a study of the penetration of water into the wheat grain, concluded that cracking from tempering possibly was the result of two types of forces, namely, a) a residual stress set up within the wheat endosperm during the maturing stage of kernel development, and b) a gradient of swelling forces produced when moisture was adsorbed into the kernel.

Henderson (11) reported that rice checking resulted from a moisture or a temperature increase. He observed the nature of crack development and found that internal fractures originated at the center of sound kernels and then progressed along the minor axes toward the outside. Rhind (12) suggested that there is a change of state in the starch of the endosperm at a moisture content of 15%. Little and Dawson (13) studied the cellular nature and the biochemical reaction of different portions of the rice kernel. A central core of smaller cells was found to be surrounded by radially oriented larger cells. The size of starch granules was found to vary markedly from the center, where they were largest, to the outer layers where they were much smaller. Barber (14) found the distribution of protein for a kernel cross-section to be higher at the periphery than at the center of the kernel.

## MATERIALS AND METHODS

Rice of the Bluebelle and Nato varieties in rough and polished forms was secured from the Texas A&M University Research and Extension Center at Beaumont. After arrival at the University, the rice was stored in a chamber maintained at 74°F. and 44% relative humidity (r.h.). The previous history of the rice from fertilization of the flower through harvesting, processing, and storage was not known. Otherwise, the rice was grown and handled according to good rice-production practices.

Experiments were conducted in an environment-controlled walk-in chamber. One-half gallon plastic freezer containers with appropriate trays and saturated salt solutions were used to equilibrate the grains in a desired environment. Dynamic r.h. systems were necessary to produce sudden r.h. changes which would cause maximum moisture stresses for a given environmental change. These systems were similar to those used by Kunze (6). Four bottles connected in series with commercial gas diffusers were used to obtain the desired efficiency. Thereafter the air was exhausted from the bottles, and passed through a filter and into an adsorption or inspection chamber.

The kernel holding device included the use of two pieces of synthetic electrical spaghetti about 1 in. long, an adhesive (Eastman 910), and two pin vices which were light and provided a rapid means of fastening the free ends of the electrical spaghetti (attached to a prepared test kernel or specimen) to the tension apparatus. A cantilever transducer beam was coupled to a Sanborn preamplifier and recorder to plot force-time curves to within ±0.1 lb. An optical comparator (Wilder, Model AF) with 20X linear magnification was used to project the areas of cross-sections of fractured kernels. A planimeter was used to measure the projected areas.

The tension apparatus consisted of a small carriage or platform which was moved vertically up and down by a lead screw attached to a reversible gear motor with 6 r.p.m. constant speed. The cantilever transducer beam was rigidly attached to the top of the apparatus frame. One of the pin vices was attached to the carriage, while the other was fastened to the transducer beam.

The rice grains were first processed through an air-separation device which removed broken grains and other light materials. Thereafter, polished rice grains were immediately inspected but brown rice required hand hulling. The grains were viewed individually and collectively under various types of light through a magnifocuser having 2.75 magnification. All deformed, immature, cracked, discolored, nonvitreous, or damaged kernels were discarded. The remaining grains were allowed to equilibrate for 28 days or more in the plastic, vapor-tight containers with the saturated salt solutions. All grain moisture contents which were determined are reported on a dry-weight basis. Weights were taken on a 0–200 g. balance (Mettler, Model B5) calibrated to 0.0001 g. For moisture determinations, the grains were weighed and then dehydrated to dry-matter content in a forced-draft air oven at 213°–217°F. for 96 hr.

Retardation times were determined by inserting individual samples (50 kernels) into the adsorption chamber. After the approximate retardation time was determined, observations for fissures were started shortly before fissuring was expected and continued at 1-min. intervals until the first fissure was observed. Immediately after the first fissuring response, the elapsed exposure time was recorded, the kernels were removed from the high-r.h. environment, their change in weight was determined, and they were dehydrated to dry-matter weight. To determine moisture adsorption rates, similar experiments with 20 kernels per sample were run, but the retardation time was subdivided into five equal-exposure intervals.

For the tensile-strength experiments with moisture-adsorbing rice, 50 kernels in the equilibrating environment were placed into a 1-dram vial which was immediately capped to limit exposure of the grain to the ambient atmosphere. Five kernels at a time were removed and inserted into the adsorption chamber, which was connected to the desired dynamic r.h. system. The time of insertion was recorded. At the end of the first time interval one kernel was removed, prepared, and subjected to tension until failure occurred. Broken parts of individual kernels were kept in an identified 1-dram vial for cross-sectional area measurements of the broken sections. The remaining four kernels were removed from the adsorption chamber at the ends of successive time intervals and subjected to tensile tests. This process was repeated for the next nine sets of five kernels each. Thus, ten readings were obtained for each time exposure interval. With five replications, each exposure interval was represented by 50 tensile-strength measurements. Results of these experiments are plotted in Figs. 5 and 6.

Specimen preparation involved two pieces of synthetic spaghetti which were attached to the ends of a kernel with the adhesive. This procedure was satisfactory for polished rice, but for brown rice the bran layers had to be removed in order to achieve adequate bonding. Specimen preparation time was approximately 3 min. As tension was applied, the recorder plotted a force-time curve. The recorder was calibrated before each experiment by hanging known weights on the transducer beam.

Parts of the kernels which had been loaded to tensile failure were placed vertically on the platform of the comparator so that the cross-sectional areas of the broken sections could be determined. The force required to pull a kernel apart was determined from the force-time curve. The tensile strength in p.s.i. was calculated by using the formula

$$S_t = \frac{F}{A}$$

Where $S_t$ is in p.s.i.
F is the force in lb.
A is the area of cross-section in sq. in.

## RESULTS AND DISCUSSION

Rice kernels, when exposed to a higher-r.h. atmosphere, do not fissure immediately but require a lapse of time, which in this research is designated as the "retardation time". In order to find the tensile strength of a kernel immediately after a moisture-adsorption period, the minimum retardation time had to be determined so that the kernels could be subjected to tensile tests before fissuring occurred. The retardation times depended on exposure r.h., variety, and the form of rice (Table I). Brown rice required more time than polished rice for an initial fissuring response. This appears reasonable because polished rice adsorbed moisture

TABLE I. PERIOD TO OBTAIN INITIAL FISSURING RESPONSE[a]

| | 86% r.h. | | | | 100% r.h. | | | |
|---|---|---|---|---|---|---|---|---|
| | Bluebelle | | Nato | | Bluebelle | | Nato | |
| Reps. | Brown | Polished | Brown | Polished | Brown | Polished | Brown | Polished |
| 1 | 80 | 26[b] | 62 | 54 | 54 | 25 | 60 | 36 |
| 2 | 75 | 27 | 62[b] | 44 | 48 | 24 | 60 | 32[b] |
| 3 | 56 | 33 | 75 | 36[b] | 50 | 21[b] | 52[b] | 35 |
| 4 | 52[b] | 32 | 66 | 36 | 45[b] | 26 | 56 | 36 |
| 5 | 70 | 30 | 71 | 58 | 46 | 21 | 57 | 34 |
| Mean | 66.6 | 29.6 | 67.2 | 45.6 | 48.6 | 23.4 | 57.0 | 34.6 |

[a] The time (min.) to obtain the first fissure in 50 grains of rice after the kernels were suddenly moved from the initial condition of 74° F. and 44% r.h. to the indicated r.h. at the same temperature.

[b] Minimum.

faster than brown rice, as is shown in Fig. 1. For short exposure periods (as used in this research) the cumulative moisture adsorbed over a period of time was found to be a straight line. If exposure had continued until the rice had equilibrated to the new environment, the latter part of the plot would have approached that of a horizontal line.

### Moisture-Equilibrated Rice

The tensile strength of equilibrated Bluebelle rice changed during storage in a given environment. For example, the following data were obtained for brown-rice samples (50 kernels) after an initial storage period of approximately 1 month in the equilibrating environment:

| | |
|---|---|
| February 20, 1969 | 1,081 p.s.i. |
| March 28, 1969 | 1,197 p.s.i. |
| April 28, 1969 | 1,217 p.s.i. |

The increase in tensile strength could have been due to relaxation of residual stresses which may have developed when the grains matured in the field, when they were dried, or when they were subjected to subsequent environmental changes. Chemical or biological changes within the kernels could have been another cause for the strength increase. However, when the time period and the conditions of storage are considered, the stress-relaxation theory appears to be the more plausible one. Grosh and Milner (10) suggested that such residual stresses may develop within the wheat endosperm during the maturing stages of kernel development.

Data for polished rice of the same variety and in an equilibrating environment indicated that the kernels gained up to 500 p.s.i. in strength within the period of

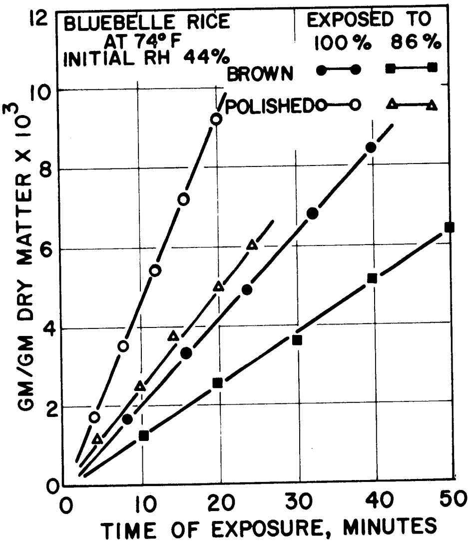


**Fig. 1. Grams of moisture adsorbed per gram of dry matter plotted against time of exposure for the conditions indicated.**

January to May of 1969. Polishing may induce stresses in addition to the residual stresses and consequently reduce the kernel strength for a period of time. These stresses may be relieved with time in an equilibrating environment and thereby cause the kernels to increase in strength.

A hypothetical analysis of stresses in two dimensions of a kernel was made in an effort to explain the physical observations. The authors recognize that the rice grain will experience three-dimensional stresses which are more complex, but hope that the current two-dimensional analyses may provide the insight for future three-dimensional approaches.

Drying of rice, both on the stalk during maturation and after harvesting, causes the outer cells of a kernel to shrink as they lose moisture. In order for moisture to flow from a kernel to the environment, a moisture gradient must exist from the center to the surface of the kernel. Hence, the inner portions of the grain will be at

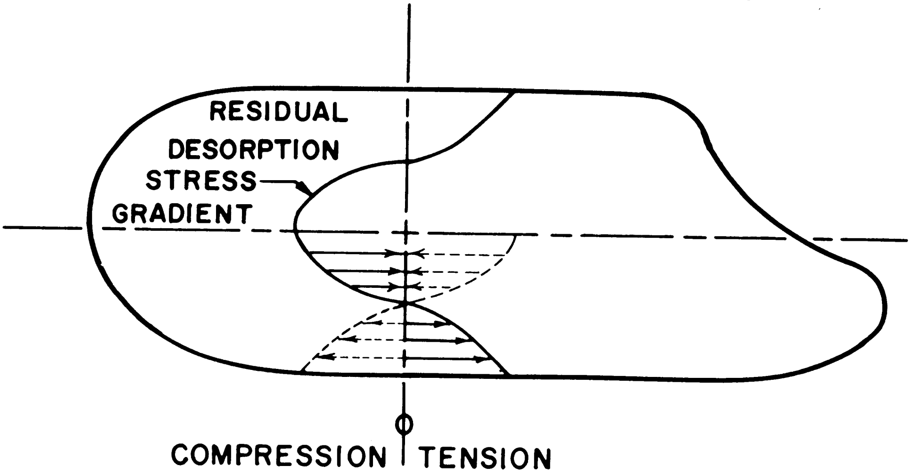


Fig. 2. A hypothetical residual desorption stress distribution within a rice kernel.

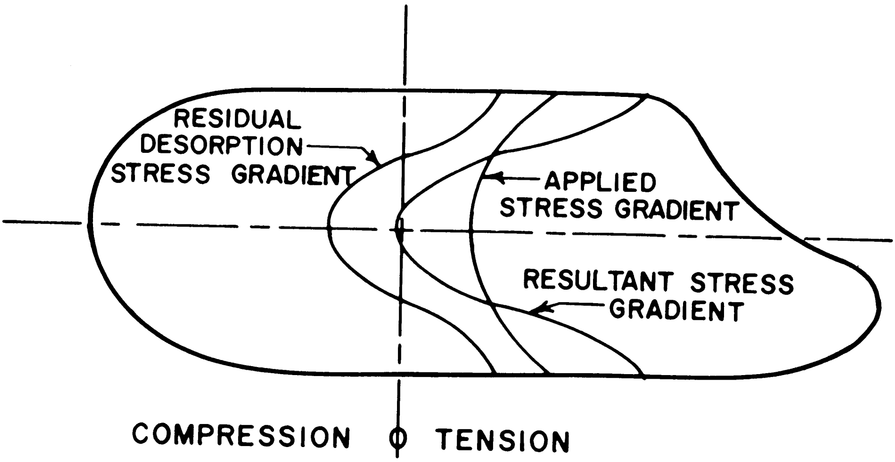


Fig. 3. Hypothetical stress distributions resulting from residual desorption stresses and externally applied tensile forces in a low-moisture kernel.

a higher moisture content than the surface portions. The result is that the surface cells tend to shrink as moisture is lost. This phenomenon causes tension at the surface and compression at the center of the grain, as is illustrated in Fig. 2. Stresses of this type may exist as residual stresses in a kernel during and for some period after a moisture loss. During moisture equilibration in a given environment, these stresses may gradually relieve themselves until a neutral-stress condition is reached. If a kernel is subjected to tension under such a residual stress condition (Fig. 3), less force will cause a tensile failure than would be necessary if the kernel were in a neutral-stress condition. The tensile stresses resulting from an applied tensile force are added to the residual tensile stresses at the surface while the compressive stresses at the center are reduced in magnitude. If the residual stresses are relieved, more applied tension would be required to cause tensile failure. This theory tends to justify the initial increase in tensile strength of the rice kernels. The authors recognize that chemical and moisture changes as well as temperature gradients and milling operations may induce other stresses which are not considered in the above analysis.

### Moisture-Adsorbing Rice

The variation of tensile strength between kernels was much more than between groups of kernels. The tensile strengths observed ranged from 455 to 2,073 p.s.i. The kernel-to-kernel variation was expected to be large since the tensile strengths of rice kernels would be expected to have a normal distribution. The initial fissuring responses of kernels after exposure are normally distributed over time, as was shown by Kunze and Hall (8). Such a hypothetical distribution for a sample is shown in Fig. 4. When a kernel fissures, the moisture-adsorbing stresses perpendicular to the plane of the fissure exceed the tensile strength of the kernel in that plane. The tensile strength of a rice kernel may, therefore, relate to its fissuring response time for a given exposure condition. Since both fissuring and tensile tests destroy the kernel structure, reliable correlations between fissuring time and kernel strength are difficult to establish. Hence, if the tensile strength of a kernel is

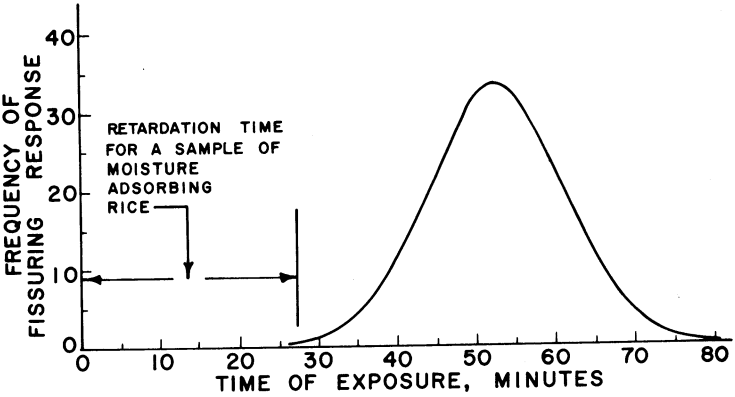


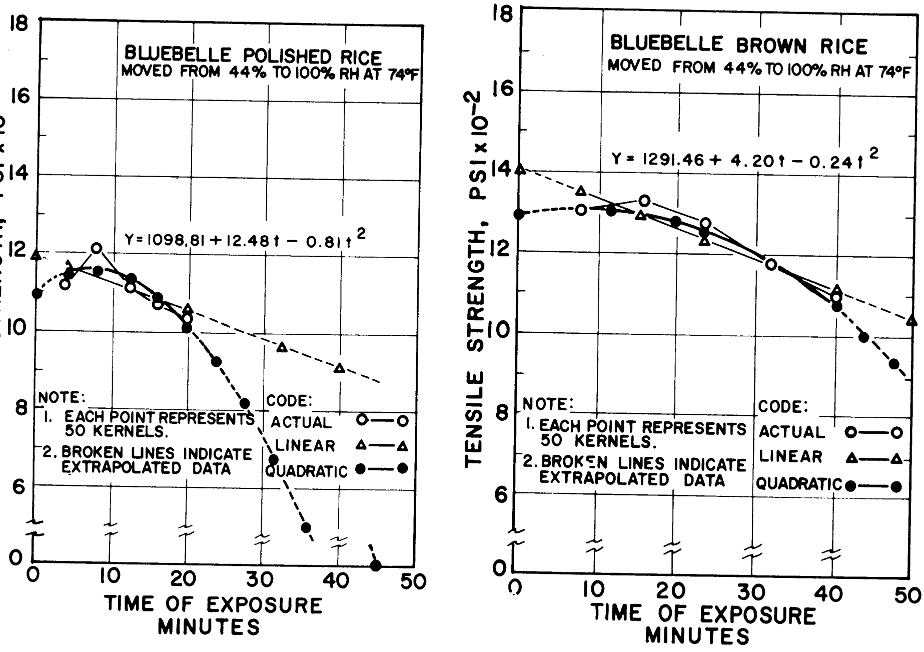
**Fig. 4. An example of a frequency distribution of fissuring responses from rice grains exposed to a higher-r.h. environment.**

assumed to be related to the fissuring response time after exposure, then the weakest kernel would fissure first and the strongest kernel would fissure last.

When a sample of kernels is exposed to a moisture-adsorbing environment, kernel strengths are not apparent from observation of the kernels. Hence, any exposed kernel could be placed into a subsample because the selection would be random. If after 20 min. of exposure a subsample was withdrawn and subjected to tensile tests, the kernel which was going to fissure after 28 min. of exposure would be expected to have less strength than the kernel which was going to fissure after 75 min. of exposure. This reasoning helps to justify the observation of a wide range of tensile strengths (p.s.i.) which were observed in a given sample of rice kernels.

Individual kernels were withdrawn at equally spaced intervals from a subsample being exposed and subjected to tensile tests. The method of orthogonal polynomials was used in the regression analysis as suggested by Anderson and Houseman (15). These equations were then reduced to include the time of exposure, t, to yield linear, quadratic, cubic, and quartic equations. Curves from these equations were plotted in an effort to secure a fit with the experimental data, Figs. 5 and 6. The solid lines indicate the actual time range for which data were collected. Beyond this range, the different curves, as estimated from the equations, are plotted with dotted lines to show their continuity.

A study of the curves for Bluebelle polished rice equilibrated at 44% r.h., before being exposed to 100% r.h. at 74°F., Fig. 5, indicates that the quadratic equation



Figs. 5 (left) and 6 (right). The influence of exposure time on the tensile strength of Bluebelle polished (left) and brown (right) rice kernels for the indicated r.h. changes.

yields points which are most likely to fit the actual strength conditions. All polished-rice kernels equilibrated in the initial environment and subjected to the above exposure would normally fissure. Therefore, any sample would have a mean response time when all grains would have fissured and the average tensile strength would be zero. In a supplementary experiment of this type the mean exposure time for all kernels to fissure was found to be 41.8 min. for the given exposure condition. This does not agree exactly with the time at which the tensile-strength value of the quadratic equation reaches zero (45.24 min.), but approximates this value better than any of the other equations. The linear equation suggests a continuously decreasing tensile strength after exposure starts. This is consistent with the thought that tensile strength decreases with exposure time but does not necessarily agree with the observed data. The negative slope, however, is not great enough to give a reasonable value for the mean exposure time at which all kernels normally would have fissured.

A study of the curves for Bluebelle brown rice equilibrated at 44% r.h. before being exposed to 100% r.h. at 74°F., Fig. 6, shows that a quadratic equation again appears appropriate. For the indicated environmental change, all rice grains would fissure. A supplementary experiment indicated the mean response time for a sample of Bluebelle brown rice to be 82.6 min. The mean response time indicated by the quadratic equation is 82.1 min. The linear equation indicates a mean response time of 198.1 min. or approximately 3-1/3 hr. Hence, the quadratic equation was again the most representative of the tensile strengths of brown rice when subjected to the indicated environmental change. The cubic and the quartic curves fit the data within the range of study, but after this time the curves show increases in tensile strengths which are not supported by research observations.

In the remaining two cases, a quadratic equation provided the most appropriate fit for brown rice (Bluebelle) equilibrated at 44% r.h. before being exposed to 86% r.h. at 74°F. The supplementary experiment indicated a mean exposure time of 120.6 min., whereas the quadratic equation predicted a 130.0-min. period. In the final case (Bluebelle polished rice at 44% to 86% r.h. at 74°F.), the observed data were such that the quadratic equation predicted an increase in grain strength after the test period. This was unlikely. The supplementary experiment with the indicated environmental change revealed that the mean response time for a sample was approximately 69.3 min. The linear equation predicted zero strength at 168.8 min., whereas the cubic equation predicted zero strength at 44.5 min. No appropriate fit was achieved when the mean response time was taken into consideration. No tensile strength tests for moisture-adsorbing grains were run with the Nato variety.

Results of the tensile tests for moisture-adsorbing rice indicated that the tensile strengths of kernels initially increased before a reduction in strength was observed. Previous work by Kunze (6) and the supplementary experiments mentioned above for the given environmental changes showed that from some point in time the reductions in kernel strength had to be continuous until the kernels fissured. The initial increase in strength was not expected and a hypothetical study was made of kernel behavior in terms of a two-dimensional stress analysis.

### Stress Analyses in Moisture-Adsorbing Rice

Convincing evidence of a critical moisture content below which rice will fissure and above which it will not fissure has been presented by several researchers. The specific moisture level at which this behavioral change occurs depends somewhat on variety and type of rice as well as on the temperature of the environment. Stahel (4) suggests 14% as the critical moisture level. Rhind (12) suggests that the starch gel is brittle below 15% moisture content but plastic at higher moisture levels. Swelling pressures of considerable magnitude are produced in kernel sections where moisture is adsorbed.

Researchers (12,13,14) have also shown that structure, texture, and chemical composition of various parts of a rice grain vary to a large extent. Generally the protein distribution within a kernel cross-section is higher at the periphery than at the center. The concentration of protein in the peripheral cells suggests that those areas are substantially stronger physically and therefore capable of resisting stresses of greater magnitude than cells in the center of the kernel.

The following assumptions are necessary for a theoretical two-dimensional stress analysis within a kernel:

a. The moisture adsorption is equal over the surface area of a kernel.

b. Stresses in the direction of the minor axis have little effect on stresses along the major axis, and hence can be neglected.

c. The kernel is infinitely long, homogeneous, and cylindrical in shape.

Using the above assumption, a rice kernel in moisture equilibrium and at stress-neutral condition could have the tensile-strength distribution as shown in Fig. 7. If a tensile force is applied by the method used in this research, then tensile stresses will develop in the kernel to give a distribution as approximated in Fig. 8. The bonding between the rice kernel and the spaghetti will produce tensile stresses first at the surface and then these will be transmitted toward the center by shear. The applied tensile-stress distribution, therefore, may be similar to the strength distribution in the rice kernel and a similar or balanced stress-strength condition across the stressed plane of the kernel could exist. In such a case the kernel could fail simultaneously at numerous points on its cross-sectional surface and tend to produce a smooth fractured plane. This type of smooth-plane breakage generally was observed in kernels which were equilibrated for a long period of time or which had come to an assumed stress-neutral condition before the tensile test.

When a moisture-equilibrated kernel was suddenly exposed to a higher r.h.,

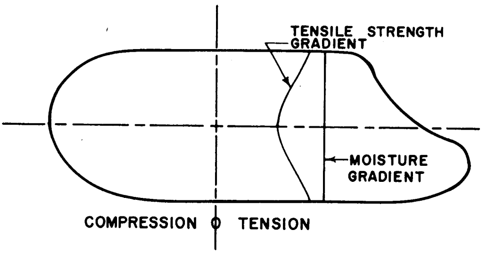


**Fig. 7. The assumed distribution of tensile strength in a kernel when it is in moisture equilibrium.**

moisture was adsorbed at the surface, which changed the moisture gradient across the kernel. This moisture adsorption caused swelling of the cells in the surface layers that further produced moisture stresses within the kernel. These stresses, which were compressive at the surface layers, were balanced by tensile stresses in the inner portions, since the kernel itself was a free body (Fig. 9). Kernel failure could occur if the compressive stresses at the surface layers developed to the extent that the resulting tensile stresses at the center exceeded the tensile strength of the

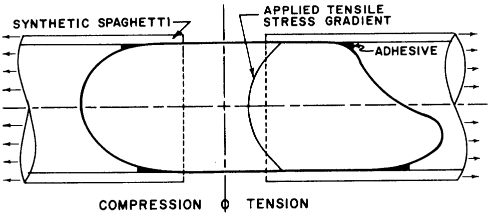


**Fig. 8. A rice kernel under tension and the resulting hypothetical stress distribution.**

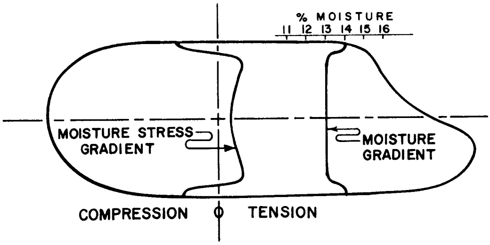


**Fig. 9. Hypothetical moisture and stress distributions during moisture adsorption by a kernel which has been exposed to a higher-r.h. atmosphere.**

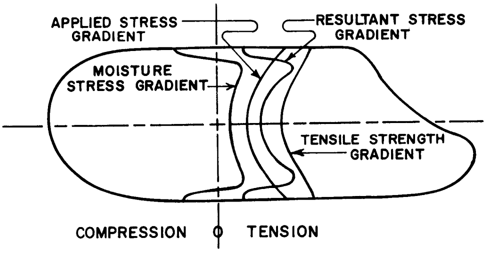


**Fig. 10. Hypothetical stress distributions developed within a rice kernel from applied tension and moisture adsorption.**

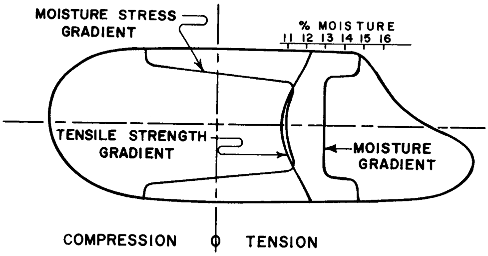


**Fig. 11. Hypothetical stress distributions within a rice kernel whose surface has reached the critical moisture level.**

central portions of the grain. If this kernel were used for a tensile test before fissuring, the applied-stress gradient and moisture-stress gradient would interact with each other and a resultant-stress gradient would develop (Fig. 10). Failure would commence when the resultant-stress gradient would intersect the assumed tensile-strength gradient at any point. The moisture stresses would cause the resultant tensile stresses to be smaller in magnitude at the surface and larger at the interior section than the stresses developed from the applied tensile force. As a consequence, a greater tensile force would be required to break the kernel than would have been necessary for a kernel which was not exposed to a higher r.h. or which was in moisture equilibrium and a stress-neutral condition. A greater calculated tensile strength was observed for many of the kernels in this nonequilibrium or transient state.

Now suppose that a kernel had been exposed to the higher-moisture environment for a longer period of time so that the surface reached the critical moisture level. In this condition the compressive stresses would be maximum at the surface just prior to the change of state of the starch. If the resulting moisture stresses develop to a magnitude greater than the tensile strength of the kernel, it would fail or fissure. The failure should occur from the inner portion of the kernel and proceed toward the outside. Figure 11 shows a stress condition where the moisture-stress gradient crossed or exceeded the tensile-strength gradient, and thus would have caused failure to start at the center. Kunze (6) and Henderson (11) observed this kind of crack development and kernel failure.

The foregoing theoretical illustrations indicate that the stress distributions can be very complex and that kernel failure may occur at any point where the resultant stress exceeds the kernel strength. The rate of moisture adsorption and its penetration into the kernel depend on the initial condition of the kernel and on the environment to which the kernel is subjected. For slow adsorption rates, the rheological properties of a kernel at storage-moisture content are such that no fissuring results. For fast rates, the kernel will fissure quite readily. Within these extremes are an infinite number of moisture-adsorption rates that can be applied to a kernel, which itself is usually in a continuously transient nonequilibrium state. Previous kernel history, time after exposure, and rate of moisture adsorption provide an infinite number of combinations, each of which could influence the tensile strength of rice at a given time. This research has attempted to give a hypothetical explanation of the data which resulted from tensile tests of individual rice kernels.

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