Temperature and Moisture Effects on Mechanical Properties of Rice

溫度與含水量對於稻米機械性質之影響

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中　文　摘　要

本研究之目的爲測定糙米在不同環境條件下的各種機械性質。試驗結果顯示糙米之機械性質因其含水量，品種及溫度而變化，其中以含水量之影響最大。一般而言，米粒强度之數値隨含水量之增加而相對減低。長粒型米之極限應力，彈性係數及韌性係數均較中粒型米爲高。而溫度對於米粒强度之影響則依品種及所受力之種類而定。

試驗前屬長粒型之 Bluebelle 種及屬中粒型之 Nato 種糙米均置放於三種溫度（68°F, 80°F 及 92°F）及四種相對濕度（11%，44%，75%及 86%）之不同組合之空氣狀態下至少三十天使其達到平衡狀態。Bluebelle 種米之平衡含水量爲 5.5%至 21.0%，Nato種米之平衡含水量則在 5.5%至 21.7%之間。

在壓縮試驗時，先將米粒之兩端切去，使其成爲柱形，然後置於兩平行面中施以垂直壓力，其加壓速度爲 0.022 in/min。大多數壓力與變形曲線之前端部份均呈一直線，然後由比例極限點起變爲彎曲直至發生斷裂。

破裂力，變形及能量可直接由壓力與變形圖上量得。極限壓縮强度，彈性係數及韌性係數可由壓力與變形曲線所得之結果計算出來。

壓縮强度依使米粒達到平衡狀態之環境條件而定。Nato 種米在垂直壓縮時需較大之力，但較少能量使其破碎。在一定溫度時，極限壓縮强度，彈性係數及韌性係數隨米粒之含水量而變，而米粒間之差異很大，所得數値之範圍如下：(1)極限壓縮强度爲 2,237至 27,348 psi，(2)彈性係數爲 38,175 至 883,347 psi，及(3)韌性係數爲 25至 3,634 in-lb/in^3。幾何平均值各爲(1)極限壓縮强度 9,178 psi，(2)彈性係數 193,938 psi，及(3)韌性係數 612 in-lb/in^3。

溫度對極限壓縮强度無顯著之影響，試驗結果指出極限壓縮强度在 24°F 之跨距內只有 3%之變化，在 80°F 時彈性係數最低，而韌性係數最高。

抗牽試驗中，牽力與變形曲線也有一段爲直線部份。在含水量高時最大强度及比例極限常爲同一點。斷裂力，變形，所需能量及比例極限均隨米粒之含水量增加而減低。變異數分析顯示品種對於抗牽强度有顯著之影響。 Bluebelle 種米之抗牽强度較 Nato種米爲大。米粒間抗牽力的差異很大。各項抗牽性質之數値範圍如下：(1)極限抗牽强度爲 253 至 2,750 psi (2)彈性係數爲 6,750 至 69,119 psi，及(3)韌性係數爲 3 至 167 in-lb/in^3。幾何平均値各爲：(1)極限抗牽强度 847 psi，(2) 彈性係數 20,485 psi，及 (3) 韌性係數 22 in-lb/in^3。在含水量高時，壓縮彈性係數約爲抗牽彈性係數之五倍，其差距隨含水量之減低而增大。對兩種不同品種之糙米而言，當溫度由 68°F 升至 80°F 時，其抗牽强度減低，但當溫度由 80°F 再上升至 92°F 時，其抗牽强度復又增加，此種現象在同一相對濕度及三種不同溫度之狀態下甚爲一致。在 80°F 時兩種品種之抗牽强度幾乎相等。彈性係數及韌性係數在抗牽試驗中以 80°F 時爲最低，92°F 時最高。

在上述試驗條件下預測極限抗牽應力及壓縮應力之迴歸方程式均已求出。由此公式計算而得之强度數値與試驗所得數値極爲相近。

1. Introduction

Since rice is consumed mostly in the form of whole unbrokem grains, processing equipment (including harvesting, drying and milling equipment) should be designed to give a high yield of unbroken polished grains. The market value of whole kernels is greater than that of broken kernels, it is, therefore, important in processing to avoid conditions that may promote breakage. In the past, much of the breakage or reduction in head rice has been attributed to mechanical damage by conveying and processing equipment. However, recent research indicates that much of this damage may have occurred because the rice kernels had previously been weakened by stress cracks caused by rapid moisture adsorption or desorption due to environmental changes during harvesting, handling and processing.

Despite the different findings over many years about the cause of rice breakage during harvesting, drying and milling, still very little basic information is known about the mechanical behavior of individual rice grains as affected by changes in environmental conditions. Studies concerning the physics of rice kernels are needed to relate stress, strain and fissuring to applied mechanical forces or to moisture and temperature gradients. When more basic data of mechanical properties become available, scientists will be able to make more intelligent evaluations of current and new methods of rice processing and milling. With knowledge of the relationships between mechanical properties of rice and environmental conditions, researchers may possibly determine a way to overcome the rice breakage problem as it exists today.

2. Objectives

The general objective of this research was to determine the mechanical properties of brown rice at different environmental conditions. More specifically, the work attempted to determine: 1) the ultimate compressive and tensile strengths, 2) modulus of elasticity, 3) proportional limit and 4) modulus of toughness.

3. Literature Reivew

Mechanical damage to agricultural products usually results from compressive loads, thus more data can be found in the literature for compression than for tensile tests. Zoerb and Hall (1960) determined some mechanical properties of individual bean, maize and wheat kernels. Comressive tests were conducted on whole kernels and core specimens prepared by cutting off the kernel ends. The ultimate compressive stress and modulus of elasticity generally decreased as moisture content of the grains increased.

Arnold and Roberts (1966) investigated the stress distributions in loaded wheat kernels with the aid of photoelastic models and developed a qualitative analogy of the stress conditions throughout the grain.

Shelef and Mohsenin (1967) studied the mechanical properties of Seneca wheat grains subjected to uniaxial compression with an Instron testing machine. Whole grains were loaded by means of parallel plates, a spherical indenter and a cylindrical indenter. Also core specimens were loaded with parallel plates. The load-deformation curve in all four compression tests was linear up to a certain load and nonlinear beyond it.

Shelef and Mohsenin (1969) later determined the effect of moisture content on mechanical properties of the horny and floury sections of dry shelled corn. Based on the results from tests, they concluded that the linear limit load, the apparent modulus of elasticity and the modulus of deformability were decreased with increased moisture content of the kernel and the major contributor to the mechanical properties observed was the horny endosperm.

The first tensile test of cereal grains was reported by Ekstrom et al. (1966). Tensile properties of individual corn kernels were determined at two moisture levels. Tension was applied to the corn kernels using hydraulic shear press and a specially constructed jig. Variations in the tensile strength depended on moisture contents. The variations were less in kernels with 15 percent moisture (wb) than in kernels with 10 percent moisture.

Kunze and Choudhury (1970) measured the ultimate 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. A large variation was observed in the tensile strengths of individual rice kernels. When rice kernels previously equilibrated at a lower relative humidity were suddenly exposed to a higher relative humidity atmosphere, the tensile strength was found to be related to the time after exposure. The ends of a rice kernel were cemented into separate pieces of synthetic spaghetti. The free ends of the two spaghetti sections were fastened with pin vices to the tension apparatus. A force-time curve was obtained by means of a cantilever transducer beam coupled to a preamplifier and recorder. Strain due to tensile force was not investigated.

4. Material and Methods

Rough rice of the Bluebelle and Nato varieties was kept in an air-conditioned laboratory before use. Individual rough rice grains were manually dehulled before being inspected. Only solid, whole, vitreous kernels were used in the experiments. Before testing, brown rice grains were equilibrated to several desired moisture levels. One-half gallon plastic containers with appropriate trays and saturated salt solutions were used to equilibrate the grains for 30 days or more in an environment chamber. An appropriate amount of rice was equilibrated at each combination of three temperatures (68, 80 and 92F) and four relative humidity levels (11, 44, 75 and 86 percent). All moisture contents were determined by drying rice grains in a force-draft air oven at 212 F for 120 hours.

The hydraulic test apparatus used was similar to that described by Mohsenin (1963). The crosshead speed for compression tests was maintained constant at 0.022 inch per minute and at 0.095 inch per minute for tension tests. The force was measured by a 6-1/2×1×1/8 inch transducer beam with strain gages mounted at points of maximum strain, Fig. 1. The transducer beam was fixed at both ends on the crosshead frame. Temperature compensation was provided with four active strain gages. The deformation of the rice kernel was measured with a 7 inch LVDT type displacement transducer with a sensitivity of 1.4 volts per inch. The tests yielded a force-deformation curve on a X-Y recorder which was calibrated by hanging known weights on the transducer beam.

Experiments were conducted in a walk-in controlled environment chamber. Temperatures were controlled to within ±1F while relative humidities were maintained at the following conditions:

Equilibrium RH for Grains	Chamber RH ±2 percent
11	22
44	44
75	60
86	60

The capability of the mechanical equipment and limitations of human comfort did not permit exact matching of the chamber environment with the equilibrating environment for the grains. Preparation and the tensile test procedure exposed the kernel to the chamber environment for a total of about 5 minutes.

Core specimens were used for all compressive tests. Specimens were made by cutting off both ends of a kernel. The cut surfaces on the core were then lightly sanded with a high speed electrical grinder to give smooth and parallel planes. An optical comparator with 20X linear magnification was used to enlarge the cross sectional areas of the core specimen ends. These were traced onto paper before a planimeter was used to measure the projected areas. Average value of the two end areas was used as the cross sectional area of the specimen. The kernels were then replaced in the same environmental condition for a minimum of 5 days before being subjected to test runs. Length, width and thickness dimensions of core specimens were measured with a micrometer and recorded. For a test, the core specimen was positioned vertically on a steel plate and a uniaxial compressive load was applied with a plunger (1/4 in. diameter) fastened to the load beam which moved up and down with the crosshead (Figs. 1 and 2).

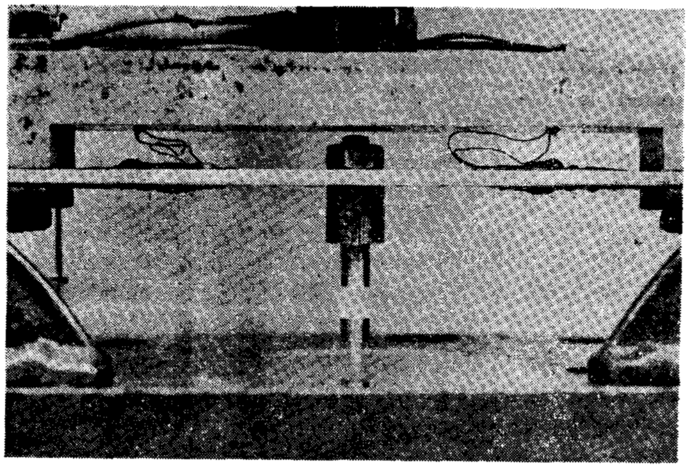


Fig. 1. The transducer beam is shown connected to the crosshead of the hydraulic test apparatus. The core specimen under the plunger is being subjected to a compression load.

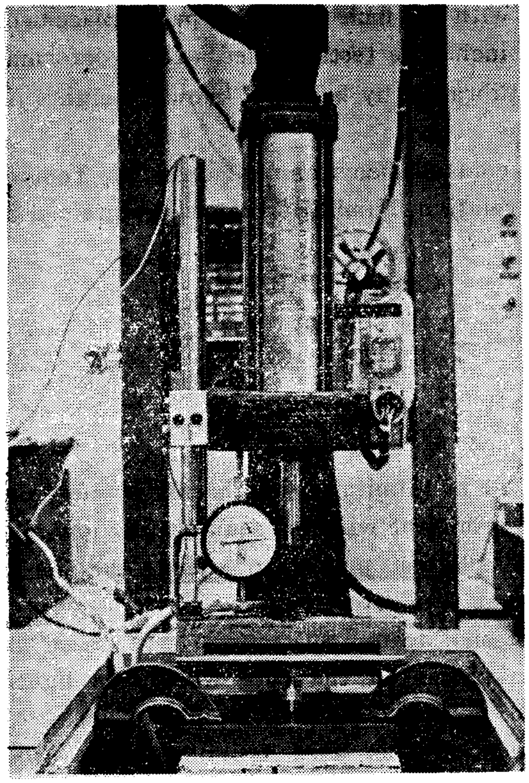
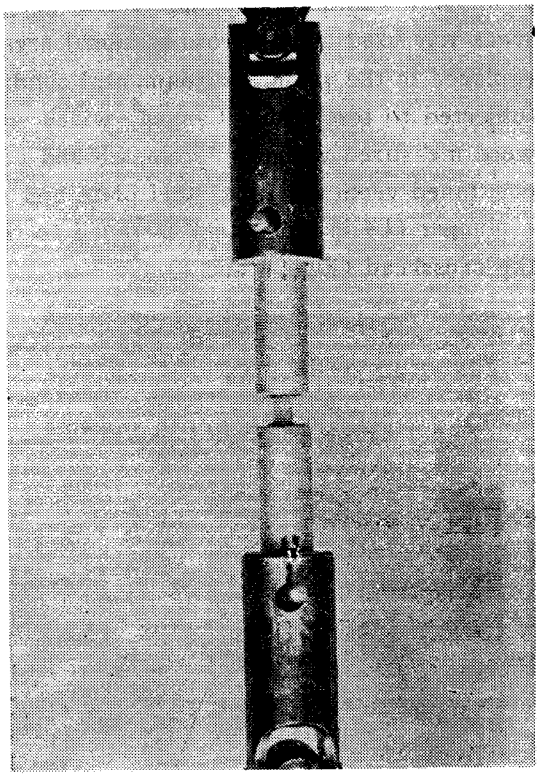


Fig. 2. The transducer beam and crosshead are shown connected to the ram of the hydraulic cylinder. The LVDT used to measure deformation is shown to the left of the cylinder.

Fig. 3. A kernel of rice is being subjected to a tensile load. The kernel is mounted in electrical connectors which are attached to universal joints to permit uniaxial loading.



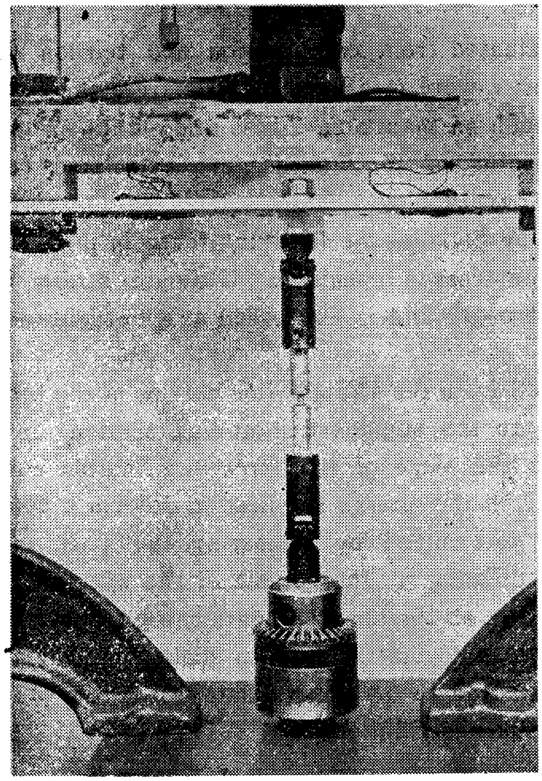


Fig. 4. The ram of the hydraulic cylinder is connected to the crosshead, transducer beam and holding devices for subjecting a kernel to tensile loading.

In tension tests. individual whole grains were prepared by using Eastman 910 cement to attach a small piece (approximately 1/8 inch long) of synthetic spaghetti to each kernel end. The exterior section of spaghetti was then bonded inside a solderless electrical connector (wire size 12–10). Tensile force was applied by pulling on the two connector ends, Fig. 3. The tension mechanism, as shown in Fig. 4, included the use of a gear chuck and two pins which provided a rapid means of linking the free ends of the connectors to the universal joints. The top universal joint was attached to the force transducer beam which move vertically with the crosshead of the machine. The bottom universal joint could be fastened rapidly to the gear chuck which was attached to the stand. This method enabled sufficiently accurate alignment of the test specimen so that uniaxial tensile force could be applied to the kernel.

The bran layer at the end portions of the kernel had to be removed in order to achieve adequate bonding. The gage length was selected as the length of the kernel exposed between the two connectors when the kernel was unstrained. The ratio of the change of the gage length to its original dimension was measured as the strain of the test kernel under tension.

Fractured surfaces 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. Uneven broken surfaces were smoothed with a razor blade before the area was traced.

5. Results

Mechanical properties of rice were evaluated from compression and tension test data. Breaking force, deformation and energy were measured directly from the force-deformation diagram. Other properties, such as maximum stress and strain, proportional limit, modulus of elasticity and modulus of toughness were calculated from data obtained from the force-deformation curves.

The ultimate strength was calculated by dividing the breaking force in pounds by the cross sectional area (sq in.) of the unstressed specimen. Ultimate strain was defined as the deformation at maximum strength and is expressed as a percentage of the original length of the core specimen.

The modulus of elasticity was evaluated from the straight-line portion of the force-deformation curve. The modulus is equal to the slope (straight-line section) of the stress-strain curve and is proportional to the slope of the force-deformation curve.

The modulus of toughness was defined as the energy required to deform a kernel to its maximum strength. The value was determined by measuring the area under the force-deformation curve (energy) and dividing by the volume of the specimen.

Analysis of variance were performed with all the observed data being transformed to logarithmic scale. The purpose of the transformation was to make the variance homogeneous and independent of the means and to make the data for each of the treatments conform more nearly to a normal distribution.

5.1 Equilibrium Moisture Contents

Equilibrium moisture contents of brown rice at three temperatures and four relative humidities were determined as follows:

Variety	Temp, F	Relative humidity, percent			
		11	44	75	86
Bluebelle	68	6.7	12.5	17.4	21.0
	80	6.0	11.7	16.2	19.3
	92	5.5	11.1	16.2	19.5
Nato	68	6.8	12.8	17.4	21.7
	80	6.1	11.6	16.5	19.9
	92	5.5	11.2	16.3	19.8

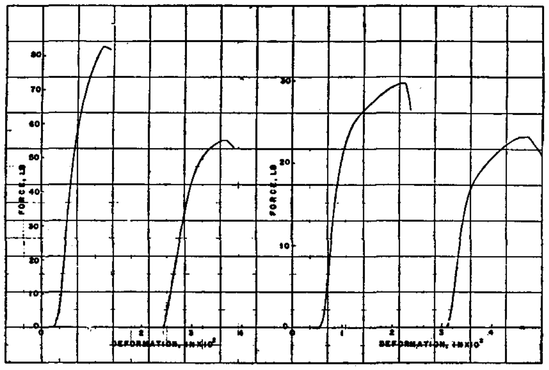


Fig. 5. Force-deformation curves for Nato brown rice (core specimens) under uniaxial compression loading at 92F and 4 moisture levels: (from left to right) 5.5, 11.2, 16.3 and 19.8 percent (db).

The results show that Nato generally exhibited a higher equilibrium moisture than Bluebelle for the same environmental condition. The difference was generally the largest at the highest relative humidity (86 percent) and the smallest at the lowest relative humidity (11 percent). For a given relative humidity, the equilibrium moisture contents, for both varieties, were lower at the higher temperatures.

5.2 Compression Experiments

Some typical force-deformation diagrams for compressive tests are shown in Fig. 5. In nearly all cases, the lower portion of the curves was straight. This indicated existence of proportionality of stress and strain over a range of stress. A small sharp curvature at the beginning of the force-deformation curve indicated imperfect contact between the end surfaces of the specimen and the mating loading plates. The force-deformation relation was nonlinear from the proportional limit until failure occurred.

Summaries of data obtained from compressive tests of brown rice are presented in Tables 1 and 2, respectively, for the Bluebelle and Nato rice varieties. Compression properties were affected by variety and the environmental condition at which the grains were equilibrated. Physical dimensions of the grains correlated highly with moisture content. Nato brown rice required more force but generally less energy to cause failure under uniaxial compression because its deformation was usually smaller than that of Bluebelle rice. Elastic limit was directly proportional to breaking force. At a given temperature, the higher the breaking force the larger was the proportional limit.

At a given temperature, ultimate strength, modulus of elasticity and modulus of toughness all depended on moisture content of the grains. Bluebelle brown rice had a higher modulus of elasticity than Nato for a given environmental condition.

Large variation between individual kernels was observed in the compressive tests. The compressive strengths of brown rice varied from 2,237 to 27,348 psi. Energy requirements in deformation up to the maximum strength points ranged from 25 to 3,634 in-lb per cu in. The highest value of modulus of elasticity was 883,347 psi while the lowest was 38,175 psi.

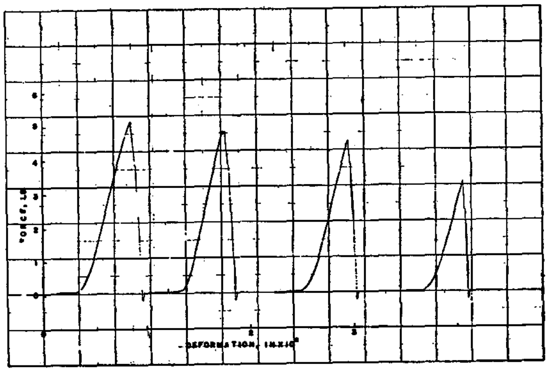


Fig. 6. Force-deformation curves for Nato brown rice under uniaxial tension at 68F and 4 moisture levels: (from left to right) 6.8, 12.8, 17.4 and 21.7 percent (db).

5.3 Tension Experiments

Characteristic force-deformation curves for tension tests are presented in Fig. 6.

Table. 1. Mechanical properties of bluebelle brown rice (core specimen) under uniaxial compression

Temp F	Moisture content %	Length in.	Width in.	Thickness in.	Cross sect. area in^2	Breaking force lbs	Breaking deformation in.	Breaking energy in-lb	Proportional limit lbs	Ultimate strength psi	Ultimate strain %	Modulus of elasticity psi	Modulus of toughness in-lb/in^3
68	6.7	0.1533	0.0816	0.0663	0.00310	55.340	0.01365	0.5065	33.607	17,846	8.98	368,416	956
	12.5	0.1612	0.0837	0.0680	0.00317	36.021	0.01430	0.4049	24.704	11,364	8.84	256,377	674
	17.4	0.1664	0.0848	0.0685	0.00353	22.004	0.01503	0.2615	13.842	6,235	9.10	147,869	355
	21.0	0.1671	0.0860	0.0682	0.00361	18.249	0.02007	0.2791	9.954	5,058	12.01	107,527	456
80	6.0	0.1593	0.0830	0 0672	0.00326	61.065	0.01281	0.5301	35.899	18,833	8.01	403,134	922
	11.7	0.1545	0.0850	0.0676	0 00385	41.808	0.01650	0.5088	24.032	10,883	10.64	230,748	768
	16.2	0.1555	0.0861	0.0685	0.00371	27.125	0.01664	0.3533	15.530	7,352	10.67	176,188	573
	19.3	0.1572	0.0869	0.0689	0.00411	20.789	0.01866	0.3064	11.630	5,085	11.97	126,773	469
92	5.5	0.1462	0.0820	0.0654	0.00339	64.330	0.01503	0.7002	40.430	19,004	10.37	428,222	1,271
	11.1	0.1639	0.0847	0.0672	0.00350	37.339	0.01337	0.4071	25.979	10,682	8.10	313,826	520
	16.2	0.1576	0.0857	0.0681	0.00360	25.523	0.01472	0.2924	16.114	7,108	9.38	216,685	458
	19.5	0.1539	0.0856	0.0677	0.00406	19.661	0.01819	0.2763	10.905	4,860	11.86	126,779	440

Note: Each value is the geometric mean of 30 kernels.

Table 2. Mechanical properties of Nato brown rice (core specimen) under uniaxial compression

Temp F	Moisture Content %	Length in.	Width in.	Thickness in.	Cross sect. area in^2	Breaking force lbs	Breaking deformation in.	Breaking energy in-lb	Proportional limit lbs	Ultimate strength psi	Ultimate strain %	Modulus of elasticity psi	Modulus of toughness in-lb/in^3
68	6.8	0.1192	0.1016	0.0669	0.00366	63.750	0.01048	0.4514	41.651	17,415	8.81	303,332	859
	12.8	0.1231	0.1042	0.0678	0.00346	43.265	0.01067	0.3480	29.770	12,534	8.65	247,958	687
	17.4	0.1266	0.1058	0.0691	0.00386	25,820	0.01099	0.1915	17 367	6,706	8.64	126,418	336
	21.7	0.1263	0.1056	0.0700	0.00369	21.927	0.01807	0.2941	11.987	5,959	14.31	102,491	619
80	6.1	0.1091	0.1008	0.0564	0.00391	74.443	0.01071	0.5159	50.237	19,129	9.85	269,506	1,242
	11.6	0.1170	0.1030	0.0674	0.00453	45.172	0.01076	0.3456	26.464	10,004	9.15	174,449	572
	16.5	0.1207	0.1070	0.0687	0.00474	31.721	0.01430	0.3355	17.324	6,723	11.91	129,436	543
	19.9	0.1183	0 1054	0.0693	0.00493	24.056	0.01718	0.3125	11.910	4,893	14.53	92,740	531
92	5.5	0.1125	0 1006	0.0652	0.00410	81.916	0.00976	0.5080	55.666	20,009	8.72	363,300	1,053
	11.2	0.1158	0.1036	0.0665	0.00407	45 890	0.00932	0.3144	32.154	11,301	8.07	243,763	577
	16.3	0.1261	0.1046	0.0675	0.00455	29.089	0.01239	0,2769	20.785	6,408	9.83	171,936	438
	19.8	0.1187	0.1055	0.0681	0.00505	23.426	0.01465	0.2504	14.915	4,657	12.36	84,185	413

Note: Each value is the geometric mean of 30 kernels.

Table 3. Tensile properties of Bluebelle brown rice

Temp F	Moisture content %	Width in.	Thickness in.	Cross sect. area in^2	Breaking force lbs	Breaking elongation in.	Breaking energy in-lb	Proportional limit lbs	Ultimate strength psi	Ultimate strain %	Modulus of elasticity psi	Modulus of toughness in-lb/in^3
68	6.7	0.0852	0.0675	0.00354	4.995	0.00505	0.01426	4.244	1,417	5.60	27,782	41 0
	12.5	0.0855	0.0678	0.00378	4.339	0.00447	0 01155	3.369	1,147	4.96	26,127	29.9
	17.4	0.0849	0.0678	0.00405	3.380	0.00292	0.00600	3.363	830	3.26	26,489	14.9
	21.0	0.0850	0.0669	0.00390	2.647	0.00253	0.00392	2.608	673	2.83	24,228	10.3
80	6.0	0.0841	0.0664	0.00387	4.177	0.00406	0.01104	3.516	1,076	4.50	27,517	26.6
	11.7	0.0841	0.0671	0.00427	3.624	0.00459	0.01090	3.001	847	5.08	19,105	23.7
	16.2	0.0850	0.0687	0.00375	2.580	0.00325	0.00530	2.580	682	3.61	19,537	14.1
	19.3	0.0860	0.0591	0.00361	1.680	0.00290	0.00311	1.680	459	3.21	15,078	8.6
92	5.5	0 0829	0.0669	0 00369	5.463	0.00461	0.01510	4.883	1,477	5.10	33,723	38.0
	11.1	0.0839	0.0673	0.00362	4.580	0.00352	0.00941	4.447	1,271	3.92	34,461	26.5
	16.2	0.0839	0.0680	0.00377	3.230	0.00431	0.00834	3.230	860	4.79	18,881	23.0
	19.5	0.0838	0.0680	0.00360	3.051	0.00302	0.00544	3.051	846	3.34	26,248	15.5

Note: Each value is the geometric mean of 30 kernels.

Table 4. Tensile properties of Nato brown rice

Temp F	Moisture content %	Width in.	Thickness in.	Cross sect. area in^2	Breaking force lbs	Breaking elongation in.	Breaking energy in-lb	Proportional limit lbs	Ultimate strength psi	Ultimate strain %	Modulus of elasticity psi	Modulus of toughness in-lb/in^3
68	6.8	0.1001	0.0673	0.00498	5.598	0.00473	0.01489	4.714	1,125	6.31	19,585	37 5
	12.8	0.1029	0.0685	0.00503	4.537	0.00450	0.01218	3.830	899	5.97	16,883	28.9
	17.4	0.1038	0.0687	0.00490	3.401	0.00299	0.00612	3.338	692	3.99	14,248	15.6
	21.7	0.1044	0.0674	0.00482	2.520	0.00242	0.00369	2.520	521	3.23	16,657	9.5
80	6.1	0.1015	0.0668	0.00451	4.348	0.00440	0.01209	3.134	963	4.89	22,773	26.0
	11.6	0 1014	0.0673	0.00440	3.947	0.00424	0.01088	2.927	894	5.67	18,484	29.1
	16.5	0.1044	0.0678	0.00460	3.128	0.00343	0.00663	2.900	682	4 57	16,123	17.7
	19.9	0.1055	0.0692	0.00473	2.415	0.00228	0.00350	2.415	506	3.05	17,055	9.0
92	5.5	0.1023	0.0661	0.00469	5.459	0.00512	0 01571	4.566	1,163	6.79	19,340	39.2
	11.2	0.1030	0.0677	0.00450	4.138	0.00431	0.01036	3.438	919	5.71	18,480	27.5
	16.3	0.1039	0.0675	0.00441	3.180	0.00419	0.00795	3.180	719	5.58	13,396	21.4
	19.8	0.1046	0.0680	0.00436	2.702	0.00279	0.00463	2.702	614	3.72	17,060	12.8

Note: Each value is the gemetric mean of 30 kernels.

The initial nonlinear region of the curve apparently was caused by friction in the universal joints and other connections. As in compression, the slope of the straight-line portion of the curves was proportional to the modulus of elasticity. At high moisture contents, the points of maximum strength and proportional limit often coincided.

The data for tension tests (Tables 3 and 4) indicate that breaking force, deformation, energy and proportional limit all decreased as moisture content of the rice grains was increased.

Ultimate tensile strengths also decreased with increasing moisture. An analysis of variance indicated that variety had a significant effect on tensile strength. Bluebelle brown rice generally had higher tensile strength and modulus of elasticity but exhibited less tensile strain than did Nato.

As in compression, the variation between individual kernels in their tensile properties was quite large. Values of tensile strength ranged from 253 to 2,750 psi. Modulus of elasticity varied from 6,750 to 69,119 psi.

6. Discussion

6.1 Effect of Moisture Content

Moisture had the greatest effect on the mechanical properties of rice. In general, all strength values were inversely proportional to moisture, ultimate tensile and compressive strengths decreased when moisture content increased, Figs. 7 and 8. Each point on the graphs represents an average of the moisture contents observed at a given relative humidity and three different temperatures. For example, the first point representing Bluebelle rice in Fig. 7 represents the average equilibrium moisture content observed for 11 percent relative humidity when samples were equilibrated at temperatures of 68, 80 and 92 F. Each sample consisted of 30 kernels and each point represents the geometric mean of 90 values. For a given moisture content, the vertical distance between the two lines represents the difference in strength between the two varieties. The Bluebelle (long grain) and Nato (medium grain) rice varieties showed no significant difference in compressive strength.

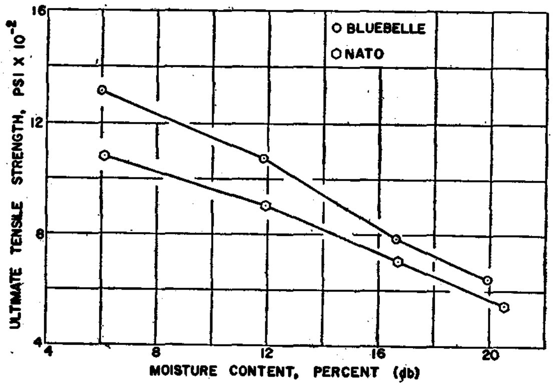


Fig. 7. The ultimate tensile strengths observed at the indicated average moisture contents. Each point represents the geometric mean of observations made at one relative humidity and three temperatures (90 individual observations).

Relationships between modulus of elasticity and moisture contents are shown in Figs. 9 and 10. The modulus in tension for the Nato variety showed a small increase at the highest observed moisture content.

At high moisture contents, the modulus of elasticity in compression was about five times the modulus under tension. The differences increased as the moisture was reduced. This indicates: 1) that a much greater stress was required in compression to produce a given strain and 2) that the stress requirement in compression to produce a given strain increased much faster than the stress requirement in tension as the moisture content of the grain was lowered.

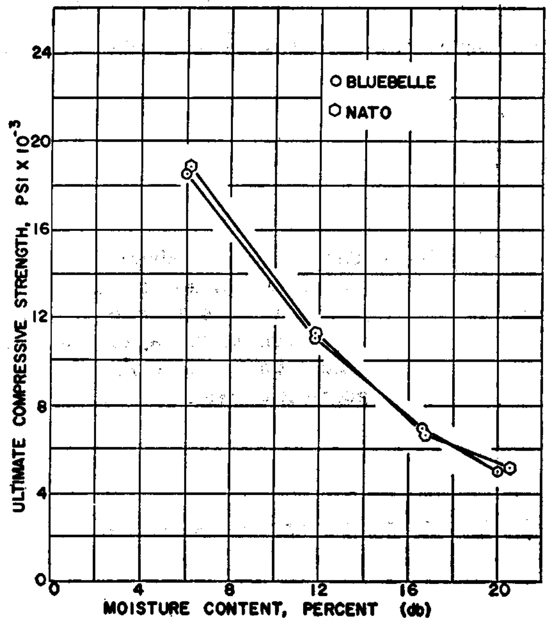


Fig. 8. The ultimate compressive strengths observed at the indicated average moisture contents. Each point represents the geometric mean of observations made at one relative humidity and three temperatures (90 individual observations).

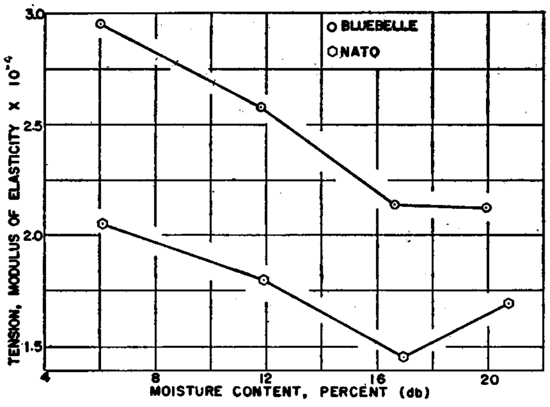


Fig. 9. The modulus of elasticity in tension which was calaulated from stress-strain observations made at the indicated average moisture contents. Each point represents. the geometric mean of 90 kernels.

Analysis of variance indicated that moisture had a highly significant effect on modulus of toughness in both tension and compression as shown by the following results:

Moisture, percent	Modulus of toughness, in-lb/in^3	
	Tension	Compression
6.1	34.1	1,039.2
11.8	27.5	627.3
16.7	17.5	441.9
20.2	10.7	483.2

These results show that as moisture increased, the modulus of toughness generally decreased.

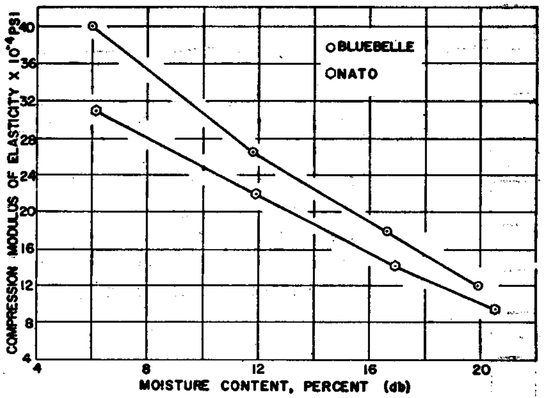


Fig. 10 The modulus of elasticity in compression which was calculated from stress-strain observations made at the indicated average moisture contents. Each point represents the geometric mean of 90 kernels.

6.2 Effect of Temperature

The tensile strength of brown rice, both varieties, decreased as the temperature increased from 68 to 80 F and increased as the temperature was further increased from 80 to 92 F, Fig. 11. This observation was rather consistent for a given relative humidity at all three temperature levels (Tables 3 and 4). The values of tensile strength for both varieties at 80 F were almost equal. Bluebelle showed a greater strength variation than did Nato. There is no apparent justification for the observed variation; but if it does exist, it could be a significant factor in rice handling and processing operations.

Temperature, however, had no significant effect on ultimate compressive strength of brown rice as shown in the following tabulation:

Temp, F	Ultimate compressive strength, psi
68	9,297
80	9,129
92	9,107

These results show that the ultimate compressive strength varied less than 3 percent within the span of 24 F.

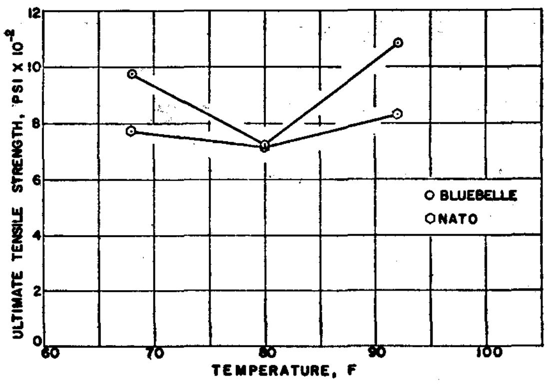


Fig. 11. Observed variations in ultimate tensile strength of rice at the indicated temperatures for the varieties shown. Each point represents four relative humidity conditions and the geometric mean of 120 observations.

The effects of temperature on modulus of elasticity for both varieties in tension and in compression were as follows:

Temp, F	Modulus of elasticity, psi	
	Tension	Compression
68	20,911	186,499
80	19,128	181,404
92	21,581	215,962

The values of modulus of elasticity were the lowest at 80 F and the highest at 92 F in both tension and compression experiments.

Temperature effect on modulus of toughness in tension and in compression are shown by the following results:

Temp, F.	Modulus of toughness, in-lb/in^3	
	Tension	Compression
68	20.6	579.9
80	17.7	666.6
92	23.9	589.7

The modulus of toughness at 80 F was the lowest in tension but the highest in compression.

6.3 *Combined Effect of Temperature and Moisture*

The logarithmic mean values of the ultimate tensile and compressive strengths were used to evaluate the combined effect of temperature and moisture. Second degree regression models were used to develop prediction equations for tensile or compressive strength. Regression analysis of mean ultimate stress values for individual varieties (brown rice) at each temperature (T) in degrees F and moisture (M) in percent dry basis yielded the prediction equations in Table 5. Strength values calculated from these equations show good agreement with observed values at the different environmental conditions. Response surfaces plotted with the calculated values are presented in Figs. 12, 13, 14 and 15.

Table 5. Prediction equations for ultimate tensile and compressive strengths for the indicated varieties

Variety	Prediction equation	R^2, %
Bluebelle	$\text{Log } S_t = 10.2819550 - 0.1794900T + (0.11172 \times 10^{-2})T^2 - 0.0129945M - (0.6472 \times 10^{-3})M^2 + (0.892 \times 10^{-4})(T \times M)$	96.4
	$\text{Log } S_c = 4.7345476 - (0.47180 \times 10^{-2})T + (0.236 \times 10^{-4})T^2 - 0.0340652M - (0.652 \times 10^{-4})M^2 - (0.665 \times 10^{-4})(T \times M)$	99.3
Nato	$\text{Log } S_t = 5.2034655 - 0\,0538533T + {}^{4}(0.3338 \times 10^{-3})T^2 - (0.10708 \times 10^{-2})M - (0.7850 \times 10^{-3})M^2 + (0.151 \times 10^{-})(T \times M)$	98.5
	$\text{Log } S_c = 5.8668728 - 0.035^{3}3433T + (0.2347 \times 10^{-3})T^2 - 0.0155590M + (0.3258 \times 10^{-3})M^2 - (0.4161 \times 10_{-})(T \times M)$	98.4

Notes: 1) Subscripts t and c designate ultimate tensile and compressive strength, respectively.
2) R is the coefficient of multiple correlation. R^2 indicates the percentage of the variation among treatment combinations which is explained by the model fitted to the data.

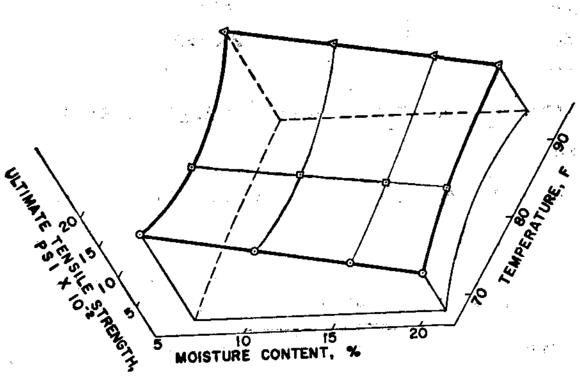


Fig. 12. Tensile strength response surface of Bluebelle brown rice.

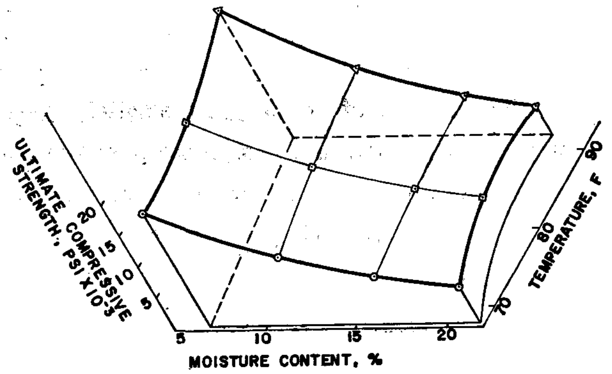


Fig. 13. Compressive strength response surface of Bluebelle brown rice.

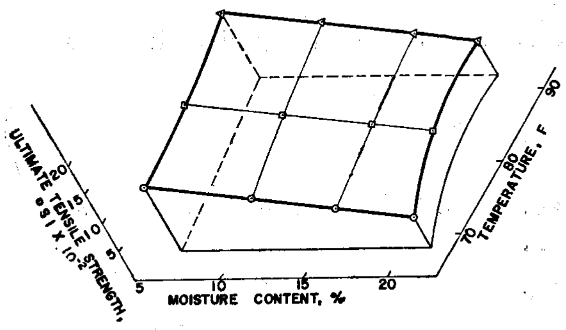


Fig. 14. Tensile strength response surface of Nato brown rice.

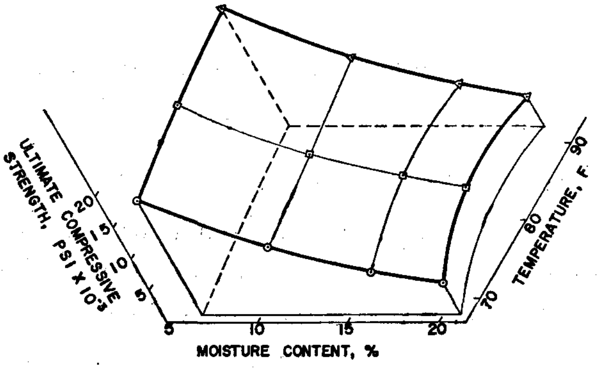


Fig. 15. Compressive stength response surface of Nato brown rice.

7. Summary and Conclusions

Investigations were conducted on the ultimate tensile and compressive strengths, modulus of elasticity, proportional limit and modulus of toughness of individual brown rice kernels at moisture equilibrated conditions involving three temperatures and four relative humidities.

The results indicate that the mechanical properties of rice are dependent on moisture, variety and temperature. Moisture had the greatest effect on the mechanical properties of rice. In general, all strength values decreased as moisture content of the grains increased. Long grain brown rice yielded higher modulus of elasticity than did medium grain rice. The temperature effect was dependent on variety and type of mechanical force which was applied to the grains.

For a given temperature, ultimate compressive strength, modulus of elasticity and modulus of toughness depended on moisture content of the grains. The geometric mean values for the three parameters were: 1) ultimate compressive strength, 9,178 psi, 2) modulus of elasticity, 193,938 psi, and 3) modulus of toughness, 612 in-lb/in^3.

Temperature had no significant effect on ultimate compressive strength. Results show that the ultimate compressive strength varied less than 3 percent within the span of 24 F. The modulus of elasticity was the lowest and the modulus of toughness was the highest at 80 F in compression experiments.

The data for tension tests indicate that tensile strength decreased as moisture content of the rice grains was increased. Variety had a significant effect on tensile strength. Bluebelle brown rice generally had higher tensile strength than did Nato. The variation between individual kernels in their tensile properties was quite large. The geometric mean values were: 1) ultimate tensile strength, 817 psi, 2) modulus of elasticity, 20,485 psi, and 3) modulus of toughness, 22 in-lb/in^3.

The tensile strength of brown rice, both varieties, decreased as the temperature increased from 68 to 80 F and increased as the temperature was further increased from 80 to 92 F. This observation was rather consistent for a given relative humidity at all three temperature levels. The values of tensile strength for both varieties at 80 F were almost equal.

At high moisture contents, the modulus of elasticity in compression was about five times the modulus under tension. The differences increased as the moisture was reduced.

Both modulus of elasticity and modulus of toughness were the lowest at 80 F and the highest t 92 F in tension experiments.

Regression equations were developed to predict maximum tensile or compressive stress within the range of environmental conditions that were studied. Strength values calculated from these equations show good agreement with observed values at the different environmental conditions.

8. Suggestions for Future Study

The following recommendations are made for future studies of the mechanical properties of rice.

1. Refinements of the experimental techniques are needed in the determination of the mechanical properties of biological materials. Conditions of the specimen, specimen size, test procedures and other factors need to be standardized to permit better comparisons of results.

2. Further investigations on the effect of temperature on tensile and compressive strengths are desirable. A larger span of temperature should be used.

3. The effect of rate of loading on the measured mechanical properties of rice should be investigated. Rate of loading is believed to affect the strength of rice.

4. Whole rice kernels should be loaded in the flat position with parallel plates to compare with the results observed from core specimens. Hertz's solution for contact stresses of two elastic convex bodies can be used to calculate the contact area, maximum compressive surface stresses and the deformation at the point of contact.

5. Elastic and plastic behavior of rice grains should be further investigated. The capability of the available equipment did not permit a rice kernel to be subjected to repeated loading-unloading cycles.

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