Effects of Flour-to-Water Ratio and Time of Testing on Sorghum Porridge Firmness as Determined by a Uniaxial Compression Test[1]

A. A. MOHAMED,[2] B. R. HAMAKER,[2,3] and A. ABOUBACAR[4]

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ABSTRACT

A compression test was conducted on specimens of porridge made from seven sorghum cultivars with different endosperm textures. Porridge was prepared using three flour-to-water (F-W) ratios and was tested at 15, 30, or 60 min after cooking. Two parameters, apparent deformability modulus (E_{app}) and yield stress (S_{max}), were compared as measures of porridge firmness. Sticky porridges, which are usually softer than non-sticky ones, scored higher in terms of S_{max} because of frictional or bonding effects. This discrepancy was absent for E_{app}, which was observed at lower strain levels. E_{app} was also more reproducible than S_{max}, and it was sensitive enough to detect differences between cultivars. The effect of the F-W ratio was highly significant, as was that of time of testing (TT) ($P < 0.001$). A cultivar × F-W ratio interaction was significant ($P < 0.01$), indicating that the F-W ratio effect was not consistent across cultivars. Most cultivars exhibited improved porridge firmness as the F-W ratio increased, but they were ranked differently at the three ratios investigated. A cultivar × TT interaction was significant ($P < 0.01$) and revealed that the rate of firmness development was higher for hard-endosperm cultivars than it was for soft ones. Cultivar ranking according to porridge firmness was also different at TTs of 15, 30, or 60 min after cooking. Firmness measured after 60 min correlated significantly with grain vitreousness and amylose content.

Sorghum porridge is a staple food in most parts of Africa and constitutes the principal part of carbohydrate intake for millions of people south of the Sahara. It is known as *tuwo, assidah, tuo, ugali, bogobe* and various other names, depending on the region. The porridge is prepared by stirring a decorticated flour in boiling water until it is completely gelatinized (Rooney et al 1986). This stiff product is consumed immediately after cooking and is usually served with a vegetable or meat sauce. Consumer acceptability of the product depends not only on taste and color but also on texture (Cagampang et al 1982, Scheuring et al 1982). Because porridge in Africa is eaten with the fingers, the textural parameter of firmness is particularly important. A good, firm porridge should hold together without yielding under finger pressure when scooped from a container (Da et al 1982).

Objective quantifications of firmness have been scarce; most were associated with sorghum improvement programs in Africa that were trying to produce new cultivars with improved pest, disease, and agronomic properties. The techniques developed for this purpose were limited by the need for rapid, simple methods that could be used to screen breeding lines. Instrumental measurement of sorghum porridge firmness was first performed by Da et al (1982) using a Precision penetrometer. They reported that a porridge of firm texture had a penetrometer reading of <7.0 mm, while a soft, unacceptable porridge had a reading of >8.0 mm. Bello et al (1990) used the penetrometer to compare the firmness of porridge made from whole and decorticated flour and concluded that decorticated sorghum flour made firmer porridge than did whole kernel flour. Although the penetrometer is a simple, easy-to-use instrument, it is an empirical technique providing a single-point measurement that is highly dependent on the type of cones used and type of weights added. More recently, Aboubacar (1992) studied porridge firmness in 16 sorghum genotypes using a penetrometer and a compression test on an Instron universal testing machine. Two parameters from the compression test correlated more significantly with sensory firmness scores than the penetrometer reading did: the slope and maximum force of the force-deformation curve, both dependent on sample dimensions and geometry.

Compression tests are commonly used to evaluate the mechanical characteristics of foods, and they constitute the basis of many empirical tests used to predict textural properties. However, well-defined, basic (fundamental) units of physics such as modulus of elasticity and yield stress can also be obtained from such tests. The advantage of using basic units is that results are independent of test geometry, thus allowing comparison of data obtained using different machines and different specimen shapes or sizes. Reporting sorghum porridge firmness in basic universal units can facilitate exchange of information between different programs evaluating new sorghum cultivars for porridge quality, and it could lead to the development of standard quality indices. A major prerequisite for the success of this approach is consistency in sample preparation and storage. Reports in the literature differ in the amounts or ratios of flour to water used by different researchers and also in sample size and time elapsed before testing.

The objectives of this study were to investigate the application of a uniaxial compression test to measure firmness of sorghum porridge made from cultivars with differing grain characteristics and to study effects of time of testing (TT) and flour-to-water (F-W) ratio on the fundamental properties that can be derived from the test. Effects of some kernel and flour characteristics on porridge firmness were also investigated.

MATERIALS AND METHODS

Grain

Seven sorghum cultivars of diverse origin were used in this study. Five of them, including a hybrid (Hageen Dura-1), were grown in 1991 in West Lafayette, IN, and two (Sepon 82, El

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[2]Department of Food Science, Purdue University, West Lafayette, IN.
[3]Author to whom correspondence should be sent.
[4]INRAN, Labo-Sols, BP 429, Niamey, Niger.

Mota) were grown in 1990 in Niger, West Africa. The cultivars exhibited a wide range of expression for physical characteristics and endosperm texture (Table I).

All grain was conditioned at 27°C and 67% rh for two weeks to a moisture content of 11.0%. Whole grain was characterized as follows: density, by stereopycnometer (Quantachrome Corp., Syosset, NY) with helium as the displacing gas according to Chang (1988); Stenvert hardness, by the method of Pomeranz et al (1985); and percent vitreousness, by a modification of the method of Kirleis et al (1984) but using a Zeiss Videoplan image analyzer (Carl Zeiss Inc., Germany).

Flour

Grain was decorticated to approximately 80% yield using the tangential abrasive dehulling device (TADD, Venables Machine Works, Saskatchewan, Canada). Preliminary work on the device determined the dehulling time required to remove 20% of kernel for each cultivar. This was recorded graphically according to the method of Oomah et al (1981) and, for a 5-g sample, ranged from 145 sec for SC283-14 to 53 sec for El Mota. The decorticated grain was then milled in a Tecator Cyclotec 1093 mill (Tecator AB, Hogana, Sweden) equipped with a 0.50-mm mesh screen.

Moisture content and water-retention capacity of flour were determined according to standard procedures (AACC 1983). Moisture content ranged from 10.6 to 11.8%. Water-retention capacity was determined at room temperature (20–22°C) using AACC method 56-10 for alkaline water-retention capacity, except that no alkali was used. The test was done in triplicate, and the results were reported as percentage of flour weight (dwb).

Starch content of the decorticated flours was determined using AACC method 76-11 (AACC 1983). The average of three replicates is reported on a dry-weight basis of decorticated flour. A spectrophotometric assay recently reported by Landers et al (1991) was used to determine amylose content in the decorticated flours. The method employs the same principle as that reported by Juliano (1971), in which iodine binds with amylose to produce a color that is measured at 620 nm, but corrects for the interference caused by the presence of amylopectin, which also reacts with iodine. Amylose content was reported as percent (dry weight) of decorticated flour (Table I). Amylose-to-amylopectin ratios were then calculated for each cultivar.

Porridge Preparation

The laboratory technique developed by Da et al (1982) for cooking small samples of sorghum flour into porridge was adopted. Three different preparations (three F-W ratios) were investigated. Flour (9.50 g, dwb) was made into a slurry using 20 ml of purified water. Then 15, 20, or 25 ml of water was heated to boiling in a 100-ml glass beaker on an electric hot plate at maximum setting. The cold slurry was then quickly poured into the boiling water. An additional 5 ml of water was used to rinse all the flour into the beaker. The porridge was cooked for 2.5 min at the maximum temperature and 2.5 min at a medium setting, for a total of 5 min, and then quickly poured into four smooth, polypropylene, cylindrical tubes (2.50 cm, i.d., 2.80 cm high) with both ends open. It was left to cool at room temperature for 15, 30, or 60 min before testing for firmness on the Instron universal testing machine. The rigid cylindrical tubes stood on a dry, smooth glass plate, thus preventing drying from the sides and bottom of the specimen. To prevent drying from the upper end, excess porridge was added on the top. At the end of the storage period, excess material was removed with a sharp wire cheese-cutter. The cylindrical porridge sample was carefully removed from the casting mold by pushing at one end with a smooth, wooden, cylindrical probe.

Porridge Firmness Measurement

Compression tests were performed on unlubricated 2.50-cm × 2.80-cm flat, cylindrical samples on a model 1132 Instron universal testing machine (0–2-kg load-cell capacity). The samples were uniaxially compressed until complete breakdown under a 8.50-cm diameter stainless steel plate at a constant deformation rate of 5.0 cm/min. Two parameters were deduced from the force-deformation curve: an apparent deformability modulus (E_{app}), determined as the engineering stress divided by engineering strain at 20% deformation (N/m^2) (Chu and Peleg 1985); and maximum yield stress (S_{max}), defined as the force at the point where the slope of the force-deformation curve crosses zero, divided by the area of the unstrained sample (N/m^2). Four replicate samples were tested in each experimental unit in a factorial design of seven cultivars, three F-W ratios, and three TT levels.

Statistical Analysis

A factorial analysis of variance was performed in which all main effects and interactions were estimated. Main effects included cultivar, F-W ratio, and TT. All main effects were considered fixed. Analysis of variance was also performed for each TT level where the main effects were cultivar and F-W ratio. Simple correlation coefficients between porridge firmness and grain and flour characteristics were also calculated.

RESULTS AND DISCUSSION

E_{app} vs. S_{max}

Data for porridge firmness in terms of E_{app} and S_{max} for three F-W ratios at 60 min after cooking are shown in Figure 1. Each point represents the average of four experimental values. The coefficient of variation between replicates for E_{app} was in the range of 1.0–11.8%. The higher figures represented cultivars P721Q (10.7%) and Hageen Dura-1 (11.8%). Low variability in the measurement indicated the high reproducibility of this parameter within samples and meant that they behaved like homogeneous, isotropic materials.

Average values of S_{max} were less consistent than those of E_{app}. Coefficients of variation for each S_{max} experimental unit ranged from 1.0 to 14.7%. P721Q had the highest variability at all three F-W ratios. In general, E_{app} and S_{max} were well-correlated for all cultivars. However, S_{max} values in P721Q and El Mota were

TABLE I
Characteristics of Seven Sorghum Cultivars Selected for Porridge Firmness Testing

Cultivar	Vitreousness[a] (%)	Density (g/mL)	Stenvert (sec)	Amylose Content[b] (%)	Starch Content[b] (%)	Water-Retention Capacity[b] (%)
SC283	91.8	1.393	28.6	25.0	75.0	181
P721N	75.1	1.364	29.9	18.8	73.5	166
SRN39	66.9	1.298	16.6	18.8	75.4	156
Sepon 82	65.1	1.347	25.9	20.7	71.0	146
Hageen Dura-1	60.6	1.353	23.0	18.9	76.0	146
El Mota	32.7	1.342	10.7	18.2	70.2	141
P721Q	17.3	1.283	13.6	17.4	72.6	126
LSD[c]	12.0	0.048	8.3	3.0	3.8	2.0

[a] Average of 30 kernels.
[b] Dry weight basis of decorticated flour.
[c] Least significant difference (0.05 probability level).

unexpectedly high (Fig. 1b) because they produced the softest porridges. One possible explanation for this is that the P721Q and El Mota porridges stuck to the compression plates during testing. Bageley et al (1985) studied the effect of bonding wheat starch gels to compression platens versus lubricating the gel-platen interface in uniaxial compression. They reported that the peak force in bonded compression was 20 times that obtained under lubricated conditions and almost four times that obtained under normal (neither bonded nor lubricated) conditions. No attempt was made in this study to quantify porridge stickiness, but we observed that porridges from P721Q and El Mota were the stickiest of the samples. According to Culioli and Sherman (1976), when the sample sticks to the compressing platen, a change in sample shape occurs during compression. Instead of a cylindrical sample becoming deformed to a smaller cylindrical sample, the sample changes shape, becoming barrel-shaped and resulting in discrepancies in the observed values. Porridge made of cultivars P721Q and El Mota attained maximum engineering stress at relatively higher deformations (>50%) than the rest of the samples

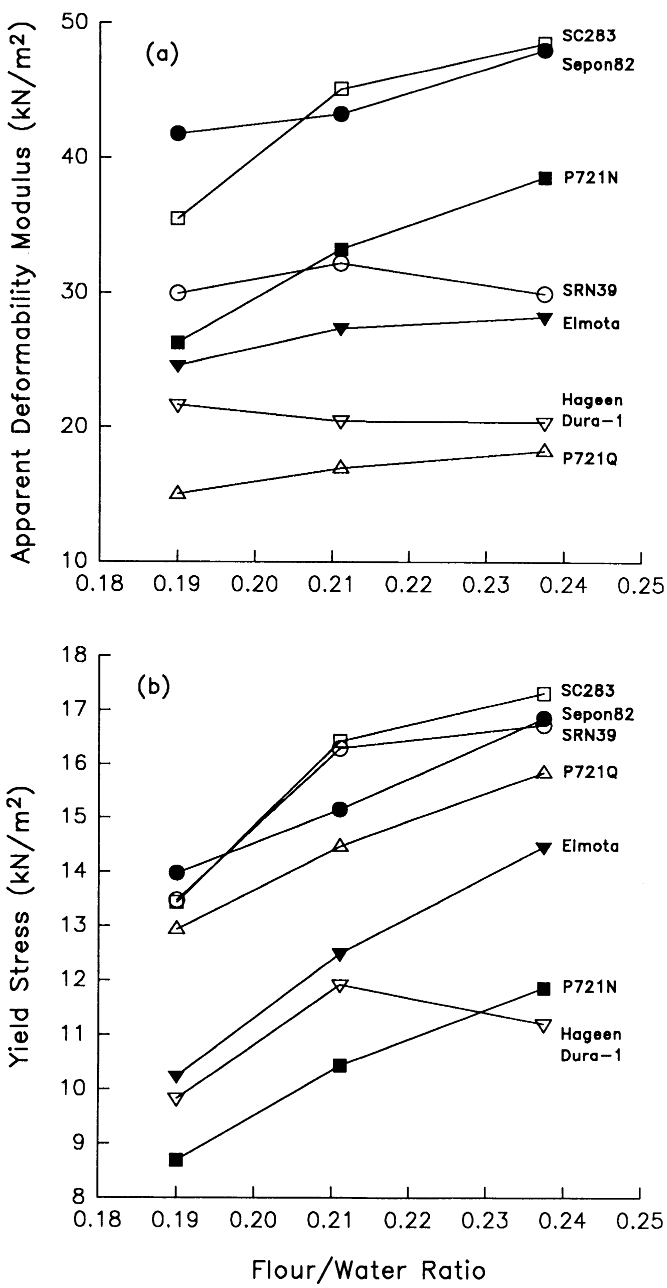

Fig. 1. Apparent deformability modulus (**a**) and yield stress (**b**) of sorghum porridge cylinders at three flour-to-water ratios, measured 60 min after cooking.

did. These two cultivars also showed barrel-shaped geometries at the latter stages of the test. When S_{max} is used to compare porridge firmness, a correction such as the one suggested by Christianson et al (1985) should be applied. However, E_{app} can be a better and simpler measure of porridge firmness, not only because it is observed at lower deformations and before changes in shape could occur, but also because there is evidence that it relates better to sensory porridge texture. Aboubacar (1992), comparing 16 sorghum cultivars for *tuwo*-making potential, found that the initial slope of the force-deformation curve in compression testing of cylindrical samples correlated more significantly with sensory firmness than with maximum force. E_{app} is a measure of the stiffness of a material (Mohsenin and Mittal 1977). S_{max} is an indication of the resistance of the food to complete breakdown. In the consumer sensory evaluation of *tuwo* reported by Aboubacar (1992), panelists in Niger, West Africa, judged firmness by applying light pressure on the sample with their fingers. This action seems more compatible with the small deformations encountered in measuring E_{app} on the Instron universal testing machine. S_{max}, on the other hand, should logically be associated with a failure type of sensory test similar to that to which the food is subjected during biting or chewing.

When comparing a large population of sorghum cultivars for porridge firmness using a compression test, care should be taken to account for frictional or bonding effects where failure parameters (S_{max}) are considered as indices of quality. With samples exhibiting stickiness, errors can arise in the observed values of S_{max} that can lead to misleading results. As reported here, E_{app} is a simpler, more reproducible means of objectively comparing porridge firmness.

Effect of Genotype on Porridge Firmness

Cultivar effect on porridge firmness was highly significant (Table II). Both E_{app} and S_{max} were sensitive enough to detect significant differences among cultivars ($P < 0.001$). Averaged over all treatments, E_{app} values ranged from 36.53 kN/m^2 (Sepon 82) to 14.32 kN/m^2 (P721Q). S_{max} values, on the other hand, varied from 12.41 kN/m^2 (SC283) to 8.23 kN/m^2 (P721N). However, because these two parameters resulted in different ranking for the cultivars, and because of the shortcomings of S_{max} discussed above, only the E_{app} was considered.

Effect of F-W Ratio

Significant differences between the three F-W ratios were obtained for porridge firmness (E_{app}, Table II). As expected, higher concentration of flour resulted in higher values of firmness in most cases (Fig. 1). It appears that changes in F-W ratio, however small (0.1900–0.2375), create environments sufficiently distinct to result in major differences in porridge firmness over a range of germ plasm.

More importantly, a significant effect of cultivar × F-W ratio for E_{app} was detected (Table II). This interaction indicates that the F-W effect is not consistent across genotypes. Although most cultivars exhibited improved firmness with increased F-W ratio,

TABLE II
Effect of Cultivar, Time of Testing, and Flour-to-Water Ratio on Porridge Firmness

Source of Variation	df	*F*-Value E_{app}[a]	*F*-Value S_{max}[b]
Cultivar	6	2,929.5*[c]	298.8*
Time	2	3,405.4*	1,902.7*
Flour-to-water ratio	2	594.7*	370.3*
Cultivar × ratio	12	89.6*	6.3*
Cultivar × time	12	86.8*	8.9*
Ratio × time	4	42.7*	9.6*
Ratio × time × cultivar	24	4.5*	0.6
Error	189	. . .	. . .

[a] Apparent deformability modulus.
[b] Yield stress.
[c] * = significant at the 0.001 probability level.

the ranking of cultivars was different at the ratios investigated (Fig. 1). For example, P721N had a lower E_{app} than did SRN39 at the 0.1900 F-W level; however, the E_{app} was higher than it was at the 0.2375 or 0.2111 F-W levels. In fact, this interaction was significant at each of the three TT investigated (Table III). Although small compared to the main effects, it requires more attention. It was present not only in terms of magnitude but in direction as well; some cultivars experienced decreases in firmness with increasing amounts of flour. The test sensitivity to subtle changes in F-W ratio could be of importance to sorghum breeders attempting to develop cultivars for better porridge quality. Comparing different breeding material for porridge firmness, using a compression test similar to the one reported here, necessitates good control of the factors involved. It is possible that when factors interact, a single-factor experiment may lead to unreliable and misleading information.

Effect of TT

Of the three main effects, TT was the most significant (Table II). Between 15 and 60 min after cooking, all cultivars showed increases in firmness (Fig. 2). Overall mean values for E_{app} were 19.19, 26.29, and 30.76 kN/m^2 at 15, 30, and 60 min, respectively, which meant that firmness continued to develop from the moment the hot paste was poured into the mold until 1 hr later; the rate of firmness development was faster in the first 0.5-hr. Regression analysis indicated a logarithmic model ($Y = a + \log X$) accounted for more than 95% of the variability in E_{app} data for most of the cultivars and for all the F-W ratios.

A cultivar × TT interaction was also significant (Table II). The rate of firmness development varied for different cultivars and for different F-W ratios (Fig. 2). At the higher (0.2375) F-W ratio, all cultivars seemed to increase in firmness at an equal rate (Fig. 2a). At the 0.1900 and 0.2111 F-W ratios, however, the seven cultivars seemed to be divided into three distinct groups; the firmer porridges had the fastest rate of firmness development. Porridges with the fastest rate of development were those made using cultivars with the most vitreous grains (Table I). It has been suggested that firming of sorghum porridge is a result of starch retrogradation as the hot paste cools to a thick gel. Waniska and Gomez (1992) measured the amount of dispersed starch in sorghum porridge at 0 min (fresh) and 60 min (aged) after cooking and concluded that this measurement revealed differences between sorghum cultivars. They found that, initially, porridge made from hard grain had similar or higher amounts of dispersed starch than that made from soft grain, but the former had less dispersed starch at the end of aging. Our results show that the rate of firming is dependant not only on cultivar type but also on the amount of flour present initially. However, all values seemed to plateau near the 60-min point (Fig. 2), indicating that this TT could be assumed as a reference point at which firmness ceases to change and at which objective measurements of porridge firmness can be compared.

Correlations with Some Grain Properties

Average values of E_{app} at the 60-min level for the three F-W ratios were used to calculate the correlation coefficients shown in Table IV. Significant correlations were found between porridge firmness and vitreousness and between porridge firmness and amylose content. The relationship between porridge firmness and vitreousness corroborates the findings of Bello et al (1990) and Waniska and Gomez (1992), who found that hard-endosperm grain produced firmer porridge. This relationship seems to be best realized at the intermediate F-W level. The role of amylose in sorghum porridge-firming is not very well understood. The amylose content per se and the amylose-amylopectin ratio both correlated significantly to porridge firmness (Table IV). Cagampang and Kirleis (1984) found a significant correlation between amylose content and sorghum gel stiffness value ($P < 0.01$). However, the alkali gel-consistency test they used had a lower F-W ratio than the one needed to make thick porridge. The time-dependent effect of amylose on aging gels was studied by Biliaderis and Zawistowski (1990) using small-strain oscillatory shear measurements. They reported that the storage modulus of pure amylose gels (potato, 1.9–8.8%, w/w) increased rapidly in the

TABLE III
Analysis of Variance for Apparent Deformability Modulus of Porridge Cylinders from Seven Sorghum Cultivars, at Three Flour-to-Water Ratios, Evaluated at Three Different Testing Times

		F-Value		
Source	**df**	**15 min**	**30 min**	**60 min**
Variety	6	871.6*[a]	1,816.3*	834.9*
Ratio	2	339.9*	453.7*	124.6*
Variety × ratio	13	61.7*	41.9*	22.1*
Error	63	...	...	...

[a] * = significant at the 0.001 probability level.

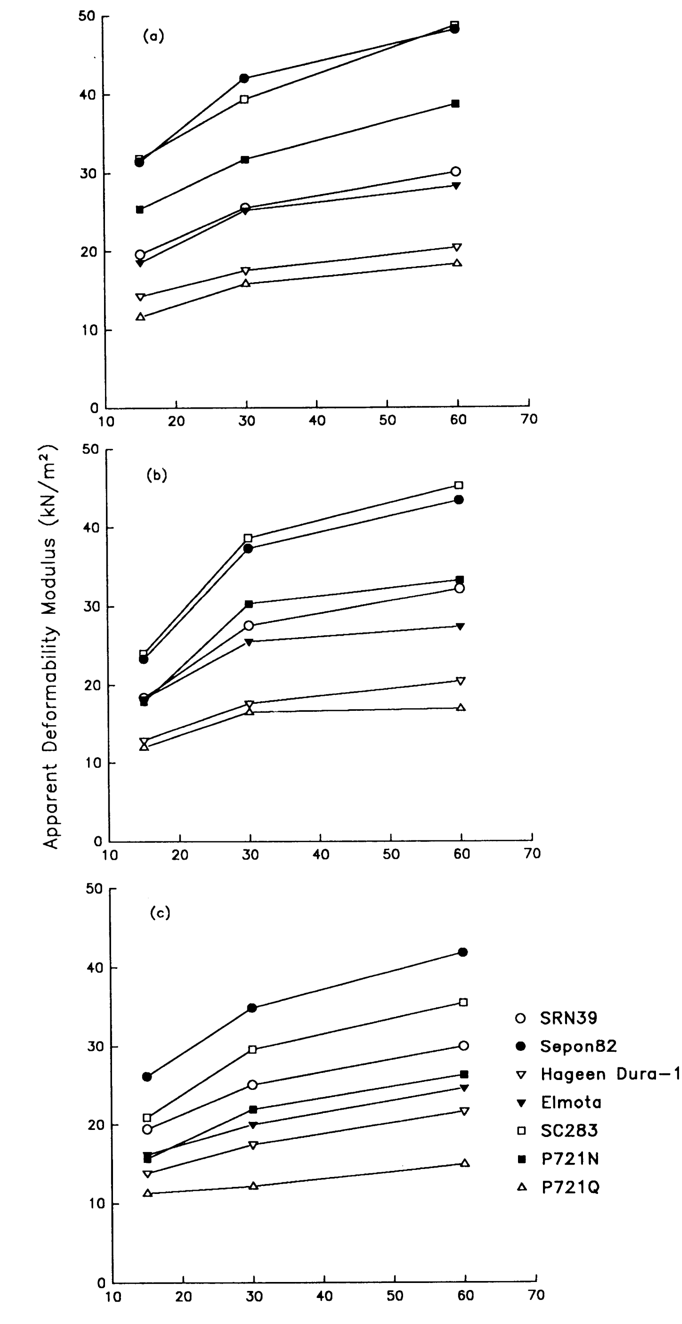

Fig. 2. Changes in porridge firmness (apparent deformability modulus) with time of testing for seven cultivars at three flour-to-water ratios: **a,** 0.2375; **b,** 0.2111; **c,** 0.1900.

TABLE IV
Simple Correlation Coefficients Between Grain and Flour Characteristics and Porridge Firmness for Seven Cultivars at Three Flour-to-Water (F-W) Ratios[a]

Characteristic	F-W1	F-W2	F-W3
Vitreousness, %	0.741	0.771*[b]	0.693
Amylose content, %	0.778*	0.801*	0.685
Amylose-amylopectin ratio	0.830*	0.838*	0.731
Water-Retention capacity, %	0.716	0.746	0.569
Stenvert hardness, sec	0.692	0.625	0.542
Density, g/mL	0.664	0.619	0.505

[a] F-W1 = 0.2375, F-W2 = 0.2111, F-W3 = 0.1900 g/ml (dwb).
[b] * = significant at the 0.05 probability level.

early stages, but showed little change upon long-term storage. Although all samples tested in this study are considered normal in terms of amylose composition (nonwaxy), it is possible that the small differences in amylose content (Table I) may have contributed to the differences in porridge quality exhibited by the seven cultivars; these small differences could also have contributed to the variability of the firmness development rates of the porridges.

CONCLUSIONS

Porridge firmness is a time-dependent, complex phenomenon that depends on endosperm texture, grain composition, F-W ratio, and TT. The uniaxial compression test investigated in this study revealed that differences were caused by small changes in F-W ratios as well as by small increments of TT. It also confirmed the reported relationship between porridge quality and grain endosperm texture. The test gives texture results in basic universal units, which should be of use to sorghum processors and breeders attempting to compare the food quality of various sorghum cultivars.

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