A Procedure to Produce Pearl Millet *Rotis*[1]

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ABSTRACT

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A laboratory procedure for preparing pearl millet *rotis* was developed. Finely ground meals produced better *rotis* than coarsely ground meals. Water absorption was critical. If the meal was finely ground and optimum absorption was used, all cultivars tested produced good *rotis*. Instron stress-relaxation curves were used to predict optimum absorption. Our data indicated that *roti* doughs are simple powder-water systems, and that cohesion is produced by water holding the powder particles together with capillary-type forces.

The term "millet" refers to many small-seeded cereals and forage grasses used for food, feed, or forage (Rachie 1975). The millets include 10 genera. This study concerns *Pennisetum americanum* (L.) Leeke, commonly known in India as *bajra*, and elsewhere as pearl millet. Pearl millet appears to have the greatest potential of all the millets. It has the largest seeds, is extremely drought tolerant, can resist high temperatures, and grows well in light soil. Thus, it will produce a crop under semiarid growing conditions.

In India and Africa, pearl millet is eaten in many forms (Vogel and Graham 1979, Subramanian and Jambunathan 1980). There are many porridges that vary in their ratio of flour to water and in whether or not they are fermented. Millet is also prepared as a rice substitute; the whole or cracked grains are decorticated and steamed until soft (Badi et al 1980). A steam-leavened flat bread called *chapati* or *roti* that is traditionally made with wheat, is made with sorghum or millet in arid and semiarid regions. Sorghum and millet do not have the gluten-forming properties of wheat flour, so doughs made from them trap gas less readily and tear more easily than do wheat-*chapati* doughs (Mason and Hoseney 1980).

Millet *roti* is traditionally prepared with stone-ground millet flour having an extraction rate of 85–100% (Rashid 1974). The meal is mixed with water and sometimes salt to produce a dough of proper consistency. The dough is then rested under a moist cloth, rolled into a ball, rolled or patted into a disk, and baked on a greaseless iron plate. The *roti* may be puffed by being placed in the fire or against a heated coal for a few seconds. Puffing is encouraged by tamping the baking dough's upper surface with a moistened cloth before placing the *roti* in the fire. Millet *rotis* generally do not puff well. Cooking time depends on the temperature of the plate and the size of the *roti*. *Rotis* are generally eaten soon after preparation.

In rural India, millet *roti* is consumed daily. Documented information on millet *rotis* is limited. Because a millet *roti* is an ersatz wheat *chapati*, wheat *chapati* quality can be used to define what a millet *roti* should be (Mason and Hoseney 1980). Aziz and Bhatti (1960) stated that a *chapati* should be flexible and have a soft, silky surface. Mouthfeel should be smooth and the *chapati* easy to chew. Ahmed (1960) observed that the thickness and texture of the *chapati* should be uniform across the diameter. Sinha (1964) stated that a *chapati* should not be leathery, tough, brittle, or gritty, and that it should be well puffed on both sides and well baked inside. Because they lack dough strength, millet *rotis* tend to be thicker and to show less tendency to puff; they are not as well baked inside as are wheat *chapaties*.

The purpose of this study was to develop a good procedure for the production of *rotis* in the laboratory, and to use the procedure to identify quality characteristics in millet meal. The study also included the development of a rheological testing procedure useful in determining optimum water absorption in millet *roti* doughs.

MATERIALS AND METHODS

Grain Samples

Several pearl millet samples were used to study the physical characteristics of millet meal. To standardize the *roti* baking procedure, pearl millet cultivar 2090 × 7107, grown in Minneola, KS, was used. Three varieties grown in Sudan (Sudan Green, Sudan Yellow, and a commercial Sudanese millet) were used to test differences in cultivars. Other pearl millet cultivars grown in Hays and Minneola, KS, during the 1980 crop year were used to evaluate various cultivars. These included: 79-2201 × 78-7024, 79-2017, × 79-4014, 70-2216 × 78-7024, 79-2161 × 79-4104, 79-2149 × 79-4104, and 79-2059 × 79-4104. Three millet samples grown in India and ground on village mills were used to compare particle fineness of traditional meals to that of experimental meals.

Preparation of the Samples

The grain was scoured on a Forestor experimental scourer to loosen and remove adhering husks. Husks and light-weight debris were separated from the grain with the Kice Aspirator. Fines and broken kernels were separated from the whole kernels by sifting the grain over a 10W screen on a Simco Gyro laboratory sifter.

Five milling systems were used to produce samples that varied in particle size and starch damage. The systems were: the Ross experimental roller mill; the Hobart coffee grinder; the Quadrumat Junior experimental roller mill; the Udy Cyclotec abrasion mill; and the Alpine pin mill.

Ross experimental roller mill. The first break rolls had 22 corrugations per inch (S/S), a roll gap of 0.015 in., and a differential of 1.25:1. The function of the break rolls was to tear open the kernel and break the stock into small particles. The second stand had rolls with 28 corrugations per inch and a differential of 1.25:1, and the roll gap was varied with consecutive reduction steps. Whole grain millet, for example, was ground until 99% of the millet meal passed through a 35-mesh screen when the Simco sifter was used. The roll gap of the second mill stand was set at 0.01 in. for the first reduction. The stock was sifted on a 35-mesh screen and the overs reground. The roll gap on the second reduction was 0.005 in. The stock was again sifted on a 35-mesh screen and the overs reground. This process was repeated with gradual reduction in the roll gap until 99% of the stock passed through the 35-mesh sieve. Whole grain millet was also ground until 99% of the millet meal passed through a 42-mesh screen. The grain was reduced as described above, except for the size of the sieve used.

Hobart coffee grinder. This type of attrition mill has several settings that allow the stock to be ground to various levels of fineness. Settings no. 5 and no. 9 were used to grind pearl millet to achieve a medium (40–60%, >65 mesh) and a coarse (60% or more, >65 mesh) distribution, respectively.

Quadrumat Junior experimental roller mill. This mill employs four rolls that provide one break and two reductions of the stock. The break utilizes rolls 1 and 2, with a differential of 2.3:1. Roll 1 has 12 corrugations per inch and runs at 1,240 rpm.

Udy Cyclotec abrasion mill. The high-speed centrifugal force of this mill pushes the grain against an abrasive disk. The severe abrasive action reduces whole grain millet to a fine powder with a single pass. A 1-mm mesh sieve allows only the finely ground meal

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to be discharged.

Alpine pin mill (160Z). This mill grinds by severe impact. Four concentric rows of rotating pins move past four concentric rows of stationary pins at 1,700 rpm. Whole grain millet was reduced to a fine powder with a single pass.

Separation of the Sample

After grinding, the particle-size distribution was determined by separation on the Alpine "air-jet" sifter. The meals were characterized arbitrarily as: percent greater than 65 mesh, percent between 65 and 100 mesh, and percent less than 100 mesh, to indicate coarse, medium, and fine particles, respectively. This sifting system produces a sharp separation based on particle size and cannot be directly compared with other less efficient, sieving systems.

Baking Method

The following represents the *roti* baking method established as the standard in subsequent testing. This method was developed using millet cultivar 2090 × 7107 milled on the Udy Cyclotec abrasion mill.

1) Fifty grams of millet flour (14%, mb) are mixed with 37 ml of tap water (74% absorption), using a spoon to achieve uniform consistency. 2) The dough is rolled into a ball and placed in a Zip-Lock™ plastic bag at room temperature for 60 min. 3) The ball of dough is then removed from the bag, lightly dusted with flour, and placed on a board covered with dusting flour. 4) The ball is rolled gently in all directions with a wooden rolling pin until it is 5–7 mm thick and nearly round. The rolling pin is then placed on 3-mm spacing bar. With the bars as a guide, the dough is rolled gently until it is 3 mm thick. Intermittent use of dusting flour on the surface may be necessary to prevent the dough from sticking and tearing. 5) A round utensil approximately 7 in. in diameter, such as an inverted plastic funnel, is used as a guide to cut the dough into a circle. Excess dough is discarded. 6) The *roti* is separated from the cutting board by gently sliding small amounts of flour under the *roti* with a spatula. Once the *roti* is loosened, it can be carefully slid onto the hand with the aid of the spatula and quickly transferred to the hot plate. Cracks or breaks in the dough should be avoided. If transferring the dough proves difficult, the *roti* should be loosened as described, and the entire board inverted to allow the *roti* to fall directly into the hot plate. 7) The metal surface of the hot plate is preheated to 200 ± 3°C and is not greased. A spatula is used to press the *roti* edges inward. 8) The *roti* is baked on side 1 for 90 sec. During the last 15 sec, an even mist of water (approx 3 ml) is applied over the exposed surface of the *roti*. 9) The *roti* is flipped and baked 90 sec on side 2. 10) The *roti* is flipped and baked for 90 sec on side 1. 11) The *roti* is flipped and baked for 90 sec on side 2. 12) The *roti* is then transferred to the simulated tandoor (Fig. 1), heated to about 35°C, with side 2 up, and the lid closed. The *roti* is heated about 30 sec, or until it is completely puffed.

Separation of Water Solubles

Water solubles were separated from millet meal by mixing 60 g of meal with enough water (100 ml) to make a slurry. The slurry was centrifuged for 10 min at 1,600 rpm and the supernatant decanted. The insoluble residue was spread on an aluminum tray and dried. To reduce the meal to its original fineness, fully dried chunks of meal were then passed through smooth rolls of the Ross experimental mill with the roll gap set at 0.005 in.

Damaged Starch

Percent damaged starch was determined using AACC method 76-30A.

Instron Stress-Relaxation Curves

Stress-relaxation data for millet doughs were obtained with the Instron Universal testing machine, model 1132. Millet doughs were prepared as previously described. Dough samples were packed evenly in a Plexiglass™ cell (37-mm diameter, 25-mm height). The dough was compressed at a rate of 0.25 cm/min. The plunger was 35 mm in diameter, allowing approximately 1 mm of clearance between the plunger and the cell wall.

The Instron was adjusted to 50 g of force per division and a chart speed of 10 cm/min. The peak stress on the dough was arbitrarily chosen to be 2 kg/cm^2; the stress curve was therefore allowed to increase 4.5 divisions. When the peak force was reached, the cross head was stopped with the plunger in place and the chart paper still running. The stress relaxation was then recorded.

The force at 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 min was recorded and these values normalized with respect to the stress-relaxation curve. We used the equation F_0t/F_0-F_t (min), where F_0 is the peak force, t is time, and F_t is the stress relaxation force at a given time (Peleg and Moreyra 1979). Stress-relaxation curves were at least duplicated.

RESULTS AND DISCUSSION

The procedure developed for the laboratory production of millet *roti* was based on studies dealing with wheat *chapaties* and personal communications with workers from India. This procedure does not necessarily duplicate *rotis* made in rural India that, of course, vary widely from place to place. Our goal was to develop a reproducible procedure that would produce a reasonable *roti*. We then wanted to use the procedure to study the properties of millet meal important in *roti* making.

Baking Characteristics

Quality guidelines for *rotis* were arbitrarily set according to those considered desirable in wheat *chapaties*. The following characteristics were considered important: minimal thickness; uniform puffing; uniformity of texture and color; golden brown surface color with intermittant darker spots where air pockets had

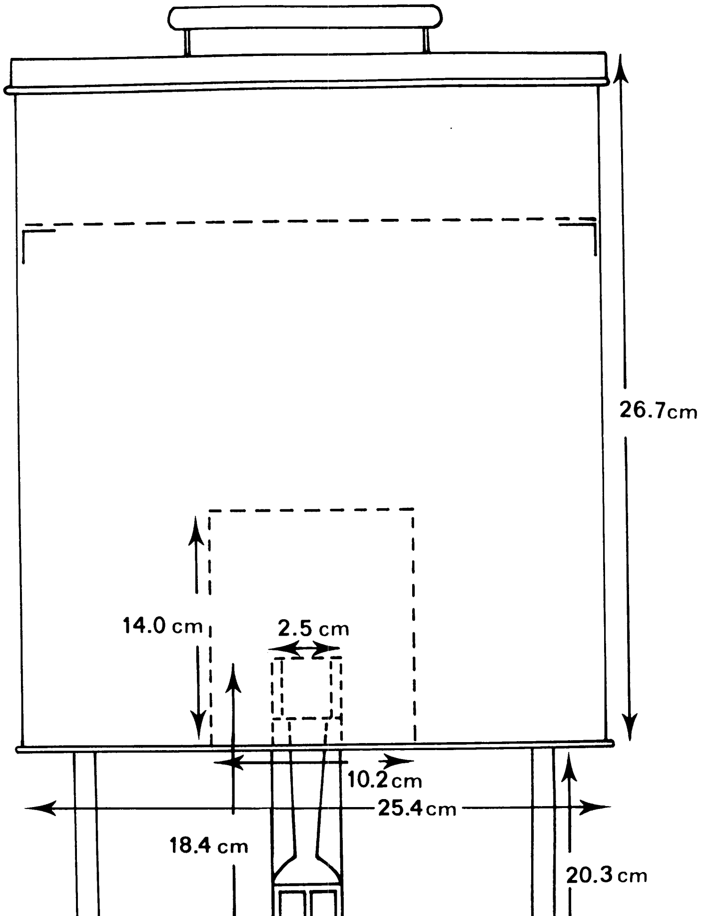

Fig. 1. Simulated tandoor cooker.

formed; and adequate internal cooking (chewy rather than raw or gummy).

According to Desikachar (1977), boiling water was necessary to give the *roti* dough sufficient cohesiveness. To test this conclusion, we prepared doughs with water that varied in 10°C increments from 30 to 100° C. The resultant *roti* doughs were not significantly different in handling or cooking quality. The heat contained in the water was probably insufficient to gelatinize starch. We chose not to investigate this further because hot water is not generally used for millet *rotis*.

To control the heat applied to the *roti* during puffing, we devised a tandoor (Fig. 1) similar to those used in India. In a tandoor, a gas heat source is shielded from the cooking area by a metal cover. That allows the heat to be distributed evenly. A wire mesh rack was placed in the tandoor. The *roti* was placed on this wire mesh rack to be puffed. Puffing occurs quickly and uniformly.

As the *roti* is cooked, starch is gelatinized and moisture diffuses to and evaporates from the exposed surfaces. When the *roti* is turned, the newly exposed surface is dried. Spraying the first exposed side with water before the *roti* is turned provides a cooling effect that reduces the amount of moisture lost during baking. The moisture inside the *roti* vaporizes when it is subjected to sudden high heat in the tandoor (approx 350° C), thus causing the *roti* to separate and puff.

Effect of Meal Particle Size on the Millet *Roti*

Whole grain millet, ground to varying degrees of fineness, produced *roti* doughs with marked differences in handling properties and texture. Meals of different particle sizes required different water absorptions and cooking times to produce an acceptable *roti*. Meals ground on the Hobart coffee grinder and Ross experimental roller mill to a coarse particle size (40% greater than 65 mesh, Table I), produced doughs that were noncohesive and difficult to mold. With coarse meals, cooking time required to produce a *roti* with a nonstarchy flavor was long. In addition, those *rotis* did not separate or puff when placed in the simulated tandoor. The finished *rotis* were gritty and dense and had little flexibility (Table II). The *roti*'s outer surface was excessively brown because of the increased cooking time and lack of bubbling on the surface (the complete surface was in contact with the hot plate throughout the cooking period).

TABLE I
Particle Size Distribution of Cultivar 2010 — 7107
Milled of Different Mill Types

	Particle Size (mesh)		
Sample	**>65 (%)**	**65–100 (%)**	**<100 (%)**
Ross, through 35 mesh	40.4	24.6	35.0
Ross, through 42 mesh	14.0	33.2	52.8
Hobart coffee grinder no. 5	56.4	17.6	26.0
Hobart coffee grinder no. 9	75.0	12.6	12.4
Pin	21.2	19.2	59.6
Udy	8.4	10.8	80.6
Quadrumat Junior	0.0	18.4	81.6

Meals with a fine particle size, such as those produced on the Quadrumat Jr. roller mill and the Udy Cyclotec abrasion mill (Table I), produced soft, cohesive doughs that could be easily molded. A cooking time of 6 min with three intermediate turns was adequate. Water vaporization in the *roti* during cooking caused air pockets or bubbles to form on the surface of the *roti*. Those slightly raised areas browned and hardened more than the rest of the *roti* surface, allowing for more flexibility in the less hardened areas. When placed into the heated tandoor, these *rotis* puffed completely, producing a pliable, nongritty texture and no raw starch flavor (Table II).

The fine particle size of meal necessary to produce a good millet *chapati* raises questions about the type and effectiveness of mills used in rural India to grind millet. Murty et al (1981) have presented data showing a fine particle size for village-produced sorghum flours. Sieve analysis showed that the pearl millet samples grown and milled in India had fine particle sizes (Table III). The manually ground sample was not as fine as the burr-mill samples, but it was still surprisingly fine.

Effect of Cooking Temperature and Time on the *Roti*

The fine meal produced with the Udy abrasion mill was used to determine the optimum cooking time and temperature. Variables studied included the cooking time before turning, the temperature of the hot plate, and the total cooking time (Table IV).

Rotis baked for 3 min on each side with only one turn after the first 3 min were hard and cracked on the outside and gummy inside. Furthermore, when those *rotis* were placed on the simulated tandoor, no puffing occurred. *Rotis* cooked at 200° C for 6 min, with a series of turns at 1.5-min intervals, were pliable and had a silky surface. When placed in high heat, these *rotis* puffed quickly and evenly.

Rotis cooked less than 6 min at 200° C were sticky inside and had a raw starch flavor. Increasing the cooking time to more than 6 min yielded *rotis* that were hard and dry and that did not puff completely.

Optimum cooking time also varied with changes in the surface temperature of the hot plate. Hot-plate temperatures less than 200° C required a longer cooking time to produce a *roti* with no raw starch flavor. These *rotis* tended to be dry inside and out, and puffed unevenly when placed in the simulated tandoor. Hot-plate temperatures above 200° C cooked the outside of the *roti* very rapidly, causing the *roti* surface to dry and crack. The insides of these *rotis* were sticky and had a raw starch flavor.

Effect of Mixing Time on the *Roti*

The effect of mixing time on the handling properties of *roti* dough and on final quality of the *roti* was studied. Mechanical mixing was tested by mixing cultivar 2090 × 7107 (ground on the Udy mill) with water in the 50-g bowl of the Brabender Farinograph for periods ranging from 30 sec to 20 min. The dough tended to become sticky with increased mixing time, but lost much of its stickiness after resting for 1 hr.

TABLE II
Effect of Meal Particle Size on *Roti* Quality Using Cultivar 2010 × 7107

Sample	**Mixing and Handling**	**Puffing**	**Texture**	**Color**	**Taste**
Ross, through 35 mesh	Semicohesive; molds with difficulty	Incomplete	Fairly flexible; gritty	Excessive browning	Raw starch
Ross, through 42 mesh	Cohesive; molds easily with some surface cracking	Varied	Flexible; fairly gritty	Fair	No raw starch
Hobart coffee grinder no. 5	Semicohesive; difficult to mold	None	Nonflexible; gritty	Excessive browning	Raw starch; earthy
Hobart coffee grinder no. 9	Non-cohesive; will not mold	None	Nonflexible; very gritty	Excessive browning	Raw starch; earthy
Pin	Cohesive; molds easily	Complete	Flexible; soft	Good	No raw starch
Udy	Cohesive; molds easily	Complete	Flexible; soft	Good	No raw starch
Quadrumat Junior	Cohesive; molds easily	Complete	Flexible; soft	Food	No raw starch

Mechanical mixing for 1 min produced *roti* doughs that were similar in handling to the hand-mixed doughs. Sticky doughs, produced by overmixing, were difficult to mold, but the final *roti* was comparable to those made from hand-mixed doughs. Manual mixing produced doughs that were easy to mold and that made good-quality *rotis*. When placed in the simulated tandoor, those *rotis* puffed completely if the water content was optimum. From these data, we concluded that mixing time was not important in *roti* dough quality, provided it was sufficient to give adequate water distribution.

Water Absorption

Production of a good-quality *roti* is dependent upon proper water distribution and consistency within the *roti* dough. Perhaps the single most important factor in *roti* dough quality is optimum water absorption. The extent and type of grinding as well as cultivar and the area where the millet was grown all tend to be governing factors in the hydration capacity of millet meal (Table V).

TABLE III
Particle Size Distribution of Millet Meal Ground on Indian Village Mills

Sample (Village)	Particle Size (mesh) >65 (%)	65–100 (%)	<100 (%)
Mahroli[a]	46.8	16.8	36.4
Churi Miyan[b]	11.6	29.6	58.8
Nechiva[b]	18.0	23.6	58.4

[a] Ground by hand between two stones.
[b] Ground on a village burr mill.

TABLE IV
Effect of Varying Cooking Time and Temperature on *Rotis* Made with Cultivar 2010 × 7107, Milled on the Udy Cyclotec Mill

Total Cook Time (min)	Time Between Turns (min)	Temperature of Hot Plate (°C)	Puffing	Texture	Color	Taste
6	1.5	150	Complete	Flexible; sticky inside	Light	Raw starch
8	2.0	150	Complete	Slightly flexible; sticky inside	Dark	Raw starch
6	1.5	175	Complete	Flexible; sticky inside	Light	Raw starch
8	2.0	175	Complete	Flexible; sticky inside	Dark	Raw starch
10	2.5	175	Cracked edges; varied	Nonflexible; sticky inside	Dark	Raw starch
6	1.5	200	Complete	Flexible	Varied; good	No raw starch
8	1.5	200	Complete	Slightly flexible; edges hard	Dark	No raw starch
4	1.0	225	Complete	Slightly flexible; sticky	Excessively dark	Outside overdone; inside raw

TABLE V
Optimum Water for Specific Particle Size and Mill Type Using Cultivar 2010 × 7107

Sample	Particle Size (mesh) >65 (%)	65–100 (%)	<100 (%)	Optimum Absorption (%)
Ross, through 35	40.4	24.6	35.0	76
Ross, through 42	14.0	33.2	52.8	74
Pin	21.2	19.2	59.6	70
Hobart no. 5	56.4	17.6	26.0	···
Hobart no. 9	75.0	12.6	12.4	···
Udy	8.4	10.8	80.6	74

The effect of different water levels on the behavior of the *roti* during mixing, handling, and baking was studied. For any given cultivar and grind of millet meal, there was one optimum water level (Table V). Excess water produced a dough that was sticky, difficult to mold, and tended to stick to the hot plate. The *rotis* produced from the wet dough were thick and wet; when placed in the simulated tandoor, they puffed unevenly, and had a moist center with a raw starch flavor.

Inadequate water produced a dough that crumbled easily and was difficult to mold and keep together on the hot plate. When placed in the simulated tandoor, those *rotis* did not puff, and the final texture was dry and inflexible.

Effect of Cultivar on the *Roti*

For any given cultivar of millet ground to equivalent particle sizes, a specific level of water is needed to achieve optimum consistency. In comparing different cultivars, all millet samples were ground on the Udy Cyclotec abrasion mill (Table VI).

The samples showing extreme differences were the cultivars grown in Sudan—Sudan Yellow and Sudan Green. Sudan Green required 78% water to produce a cohesive dough with good molding and cooking properties. At that water level, the dough was rubbery and firm, molded easily, and lacked the typical gritty characteristics seen in most millet cultivars. Sudan Yellow, on the other hand, required only 74% water. It yielded a very soft, sticky dough that produced a good-quality product upon cooking. The *roti* was flexible and puffed completely.

All cultivars tested produced good-quality *rotis* if the meal was ground to sufficient fineness and if optimum absorption was used. Handling properties varied in degrees of stickiness, but the final products were acceptable.

The molding and baking properties of a *roti* dough improve as the particle size of the meal is reduced. Millet meals ground from one sample to give more than 40% of particles greater than 65 mesh (measured on the Alpine sieve) produced poor-quality *rotis*. Meals containing 65% or more by weight of particles less than 100 mesh gave acceptable *rotis* if optimum absorption was used. Meals containing 35–55% of particles less than 100 mesh fall into an ambiguous area. Good-quality *rotis* can be produced from meals with a large range in particle size. Generally, as the particle size is reduced, the percentage of damaged starch in the sample is

TABLE VI
Optimum Water Content for Different Cultivars Ground on the Udy Mill

Cultivar	Particle Size >65 (%)	65–100 (%)	<100 (%)	H_2O Absorption (%)
2090 × 7107	8.4	10.8	80.6	74
79-2071 × 79-4014	17.2	20.0	62.8	72
79-2161 × 79-4104	15.0	16.2	68.8	76
Commercial	8.1	17.2	74.4	72
Sudan Green	1.2	10.4	88.4	78
Sudan Yellow	0.8	9.2	90.0	74

TABLE VII
Starch Damage of Meals Produced From Cultivar 2010 — 7107 Ground on Different Mills

Sample	Particle Size (mesh) >65 (%)	65–100 (%)	<100 (%)	Starch Damage (%)	H_2O Absorption (%)
Udy	8.4	10.8	80.6	3.77	74
Quadrumat Junior	0.0	18.4	81.6	2.13	76
Ross, seven passes	14.0	33.2	52.8	2.09	76
Ross, five passes	40.4	24.6	35.0	2.05	74
Pin	21.2	19.2	59.6	1.56	70

increased. Damaged starch value for meals ground in a series of mills is shown in Table VII. Starch damage tended to increase with reduced particle size, but, as can be seen with the pin-milled meal, particle size reduction does not necessarily increase starch damage. There was no obvious trend in increased water absorption with increased starch damage. The pin mill produced a much finer flour than did the Ross mill, but the optimum water absorption decreased significantly. Thus, starch damage does not appear to affect *roti* quality.

Effect of Separating the Water Soluble Fraction of Millet

The importance of the water-soluble fraction of millet meal in *roti* quality was studied. *Rotis* produced with "soluble-free" flour were slightly sticky, but the finished *roti* was soft and flexible and puffed completely. The *rotis* produced with the soluble-free flour were comparable to those produced from a completely reconstituted flour. This suggests that the soluble fraction in millet meal does not play a major role in the physical properties of the *roti*. The dough-forming properties must, therefore, involve an interaction between the insoluble fraction of millet meal and water.

This observation suggests that the interaction between millet meal and water may be similar to that in an inert powder-water system. In this type of system, the physical interactions between powder particles and water is of a capillary type: strong surface bonds form at the powder-water interface (Weyl and Ormsby 1960). Water becomes the continuous phase by forming a liquid film that results in a rigid system. Peleg and Moreyra (1979) noted that finely ground powders are in close contact with one another, forming a series of pores that determine the volume of liquid required to incorporate the water into the film system.

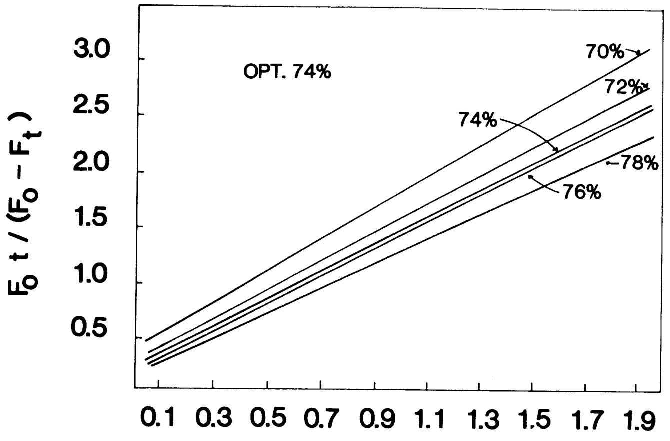

Fig. 2. Normalized stress-relaxation curves for *roti* dough produced from one sample containing various levels of water.

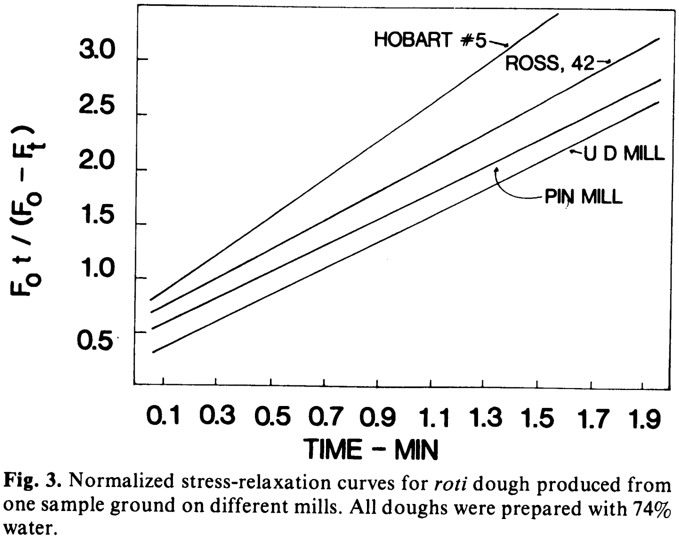

Fig. 3. Normalized stress-relaxation curves for *roti* dough produced from one sample ground on different mills. All doughs were prepared with 74% water.

The Effect of Moisture on Stress Relaxation

Millet cultivar 2090 × 7107, grown in the United States, was ground on the Udy Cyclotec abrasion mill, and its optimum absorption determined through preparation of *rotis*. A series of doughs was mixed in which water content was varied from 4% below optimum to 4% above optimum, in 2% increments (Fig. 2).

The wet dough demonstrated more liquid properties from a rheological point of view (Peleg and Moreyra 1979). Thus, a sample that is too wet will give a low slope. The observed change in slope indicates that wet dough is more deformable and better able to reflect physical changes because of internal flow and rearrangement of liquid bridges.

The dry dough (higher slope), on the other hand, was more resistant to deformation as well as to the relaxation changes that occurred under given stress. Because of liquid bridging, the flow properties were reduced, and the compacted particles demonstrated more solid properties.

The Effect of Particle Size on Stress Relaxation

Cultivar 2090 × 7101 was ground to various levels of fineness. Coarsely ground meals were produced by grinding on the Hobart attrition mill. Progressively finer fractions were produced with the Ross experimental roller mill, Alpine pin mill, and Udy Cyclotec mill. Each sample was mixed with 74% water, which was optimum for the most finely ground meal (ie, that meal ground on the Udy Cyclotec mill), and the normalized curve of stress relaxation (Fig. 3) determined.

Meals with a larger particle size gave stress-relaxation curves similar to those obtained with dry doughs; flow properties were reduced, and the particles demonstrated more solid properties. Peleg's normalization of the stress-relaxation curve made it possible to compare data between materials, but it did not eliminate the influence of physical characteristics within a given sample (Peleg and Moreyra 1979). As shown in Table VII, those millet meal samples vary not only in particle size, but also in starch damage.

The Effect of Cultivar on Stress Relaxation

Seven varieties of millet, grown at Hays and Minneola, KS and one commercial Sudanese cultivar, were milled on the Udy Cyclotec abrasion mill. Particle size of those meals was tested on the Alpine sifter and found to be similar.

Each cultivar was mixed with 74% water, and its stress-relaxation pattern determined. The normalized curves of the seven varieties formed a fan-shaped graph (Fig. 4).

The two cultivars at the extreme ends of the fan shape (nos. 12 and 20) were studied further by varying water levels and obtaining

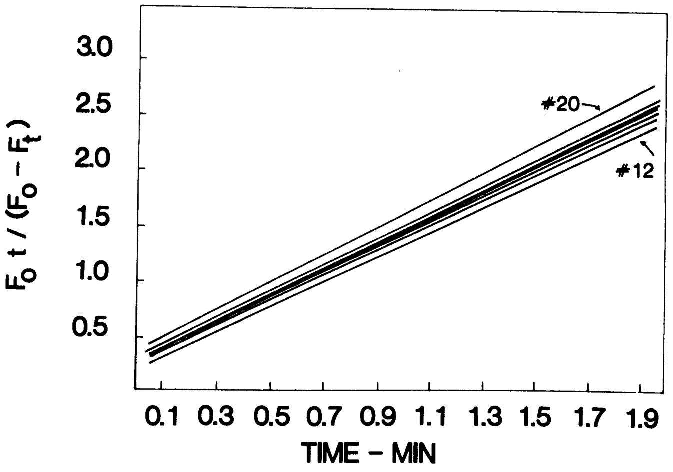

Fig. 4. Normalized stress-relaxation curves for seven different millet cultivars. All meals were ground on the Udy mill, and all *roti* doughs contained 74% water.

TABLE VIII
Particle Size Distribution for Freeze-Dried Doughs

	Particle Size (mesh)		
Sample Millet	**<65 (%)**	**65–100 (%)**	**>100 (%)**
Before dough preparation	14.0	33.2	52.8
After dough preparation	21.2	26.4	52.4

separate stress-relaxation curves for each cultivar at a number of water levels. Each cultivar produced a fan-shaped graph similar to those shown in Fig. 2.

Optimum absorption was determined by making *rotis* at varying moisture levels. When superimposed, the normalized stress-relaxation curves of differing cultivars at optimum absorption fell within a narrow range with regard to both slope and y-intercept. When these cultivars were compared to varieties grown in Sudan and to the American-grown cultivars studied earlier, all varieties tested had an optimum absorption that fell within a narrow range of slope and y-intercept.

Freeze-Dried Doughs

If the doughs produced are, as suggested above, dry powder-water systems, then it follows that if the water is carefully removed by freeze-drying, the dough should revert to a dry powder. In addition, the particle-size distribution should be essentially the same as the original meals. Doughs were prepared, freeze-dried, and lightly ground with a wooden rolling pin. The particle-size distributions of the freeze-dried meals were similar to those meals before the doughs were prepared (Table VIII). In general, the data support our conclusion that these doughs are essentially powder-water systems, with capillary forces being the main forces holding the doughs together.

CONCLUSION

It is well known that pearl millet does not have the dough-forming properties found in wheat flour. We must look elsewhere for an explanation of the cohesive properties of millet *roti* doughs. The two critical factors in developing those cohesive properties were particle size and water absorption. Factors having only a minor influence of the cohesive properties were amounts of mixing, cultivar, water solubles, and starch damage. Regardless of the other factors, if particle size was sufficiently small and water absorption correct, a cohesive dough was obtained.

The above observation suggests that millet *roti* doughs obtain their cohesive properties from the interaction of millet meal and water. The millet meal acts essentially as an inert powder. Water is, then, the continuous phase and holds the particle together by capillary forces. Similar forces are responsible for the cohesive properties of wet sand and of mud pies.

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