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THEORIES OF WHEAT HARDNESS AND THE METHODS OF ITS MEASUREMENT

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INTRODUCTION

Hardness is an important quality characteristic of wheat throughout the world. During the 1980's, it has attained the status of a critical factor in classifying wheat cultivars in some major exporting countries. Although GREENAWAY(1969) has defined hardness as resistance of kernels to deformation by outside forces, there is no simple definition for hardness, and, on the basis of the numerous hardness tests used, several arbitrary definitions could be formulated.

Grain hardness affects the milling behavior of wheat and the suitability of the resulting flour for a given end-use. Hard wheats require more conditioning (higher moisture levels and longer time) and produce coarser particles than do soft wheats. Coarse particles flow more readily than fine ones, leading to better

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bran clean up and higher extraction rates at acceptable color levels. Also, hard wheat flours contain a significant amount of mechanically damaged starch granules resulting in high water absorption, which is of considerable importance in baking processes (MOSS, 1978). Soft wheats require less energy to be reduced into flour and, hence, contain lower amounts of damaged starch than hard wheats. Their flours are more suited for pastry, cake, or cookie processes (STENVERT, 1974). Consequently, grain hardness is important to weat processing.

THEORIES OF WHEAT HARDNESS AND ITS GENETIC CONTROLS

Adhesion theory

The strength of adhesion between starch and proteins (SIMMONDS, 1972) varies between hard and soft wheats. This adhesion theory was suggested by BARLOW et al (1973a), after they showed no significant varietal differences in the hardness of starch granules and storage protein fragments from hard and soft wheats. The nature or amount of cementing material at the interface area between proteins and starch granules appears to determine the degree of hardness (BARLOW et al.,1973, SIMMONDS et al., 1973).

Although adhesion beteween starch and proteins is an important aspect of hardness, it has proved difficult to implicate any specific compound as the adhesive substance (SIMMONDS et al., 1973). Thus the suggestion that the genetic control of grain hardness could be expressed through the amount and composition of the cementing material, as suggested by BARLOW et al (1973a), is quetionable.

Scanning Electron Microscopy has been used a major tool to support the adhesion theory (HOSENEY and SEIB, 1973; SIMMONDS, 1974). In hard wheats, rupture of the endosperm occurs predominantly along cell walls. When breakage through cell contents occurs,the fracture line goes through both starch granules and the protein matrix. With soft wheats, however, adhesion between protein and starch is weaker and the fracture occurs preferentially through the endosperm cells, producing much lower starch damage than in hard wheats. Figures 1, 2, and 3 illustrate these findings.

The chemical nature of the interface material is quite complex. It contrains essentially water-soluble proteins associated with carbohydrates in a ratio 2 : 1

(BARLOW et al., 1973a, SIMMONDS et al., 1973). The carbohydrate moiety gives rise, upon hydrolysis, to glucose, maltose and other oligosaccharides whose presence might indicate trace contamination with starch. Most of the proteins in this region of the endosperm are tought to be enzymes associated with starch granule biosynthesis in the developing grain (BARLOW et al.,1973b). These proteins have mobilities similar to those of water-soluble gliadins (SIMMONDS, 1974). Other reports considered the soluble material to have low molecular weight (less than 700 daltons). Recently, these starch granule proteins were extracted at 50 C with 1% (w/v) sodium dodecyl sulfate (SDS) and fractionated by high resolution SDS-polyacrylamide gradient gel electrophoresis (GREENWELL and SCHOFIELD, 1986

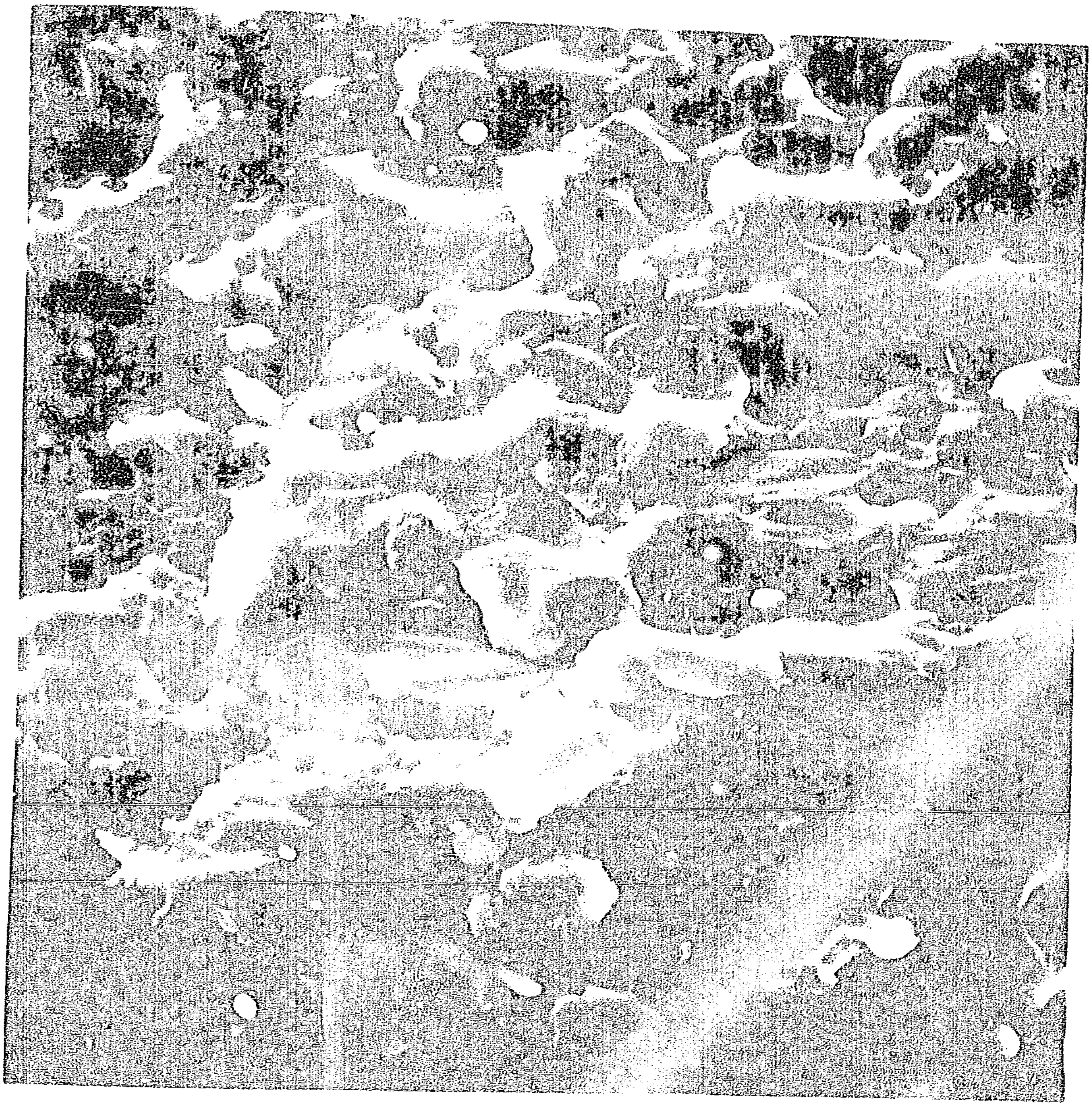

Fig . 1: S.E.M. of a fractured durum wheat endosperm (from (7))

A number of proteins were detected. Their molecular weights ranged from a few thousands to about one hundred thousand Daltons. The smaller members of this protein family were easy to extract and were assumed to be associated with the surface of starch granules. Consistent positive association was found between the presence of a 15 KD (Kilodaltons) protein band and endosperm softness, in about 150 cultivars analyzed. HOSENEY (1987) reported that the number is now over 300 cultivars and suggested that the protein may interfere with the starch and protein interaction. This agrees with the adhesion theory. The relationship has been found to also hold for moroccan wheats (BAKHELLA, 1988 ; BAKHELLA, et al., 1990). The 15 KD band in the soft cultivar Pinyte

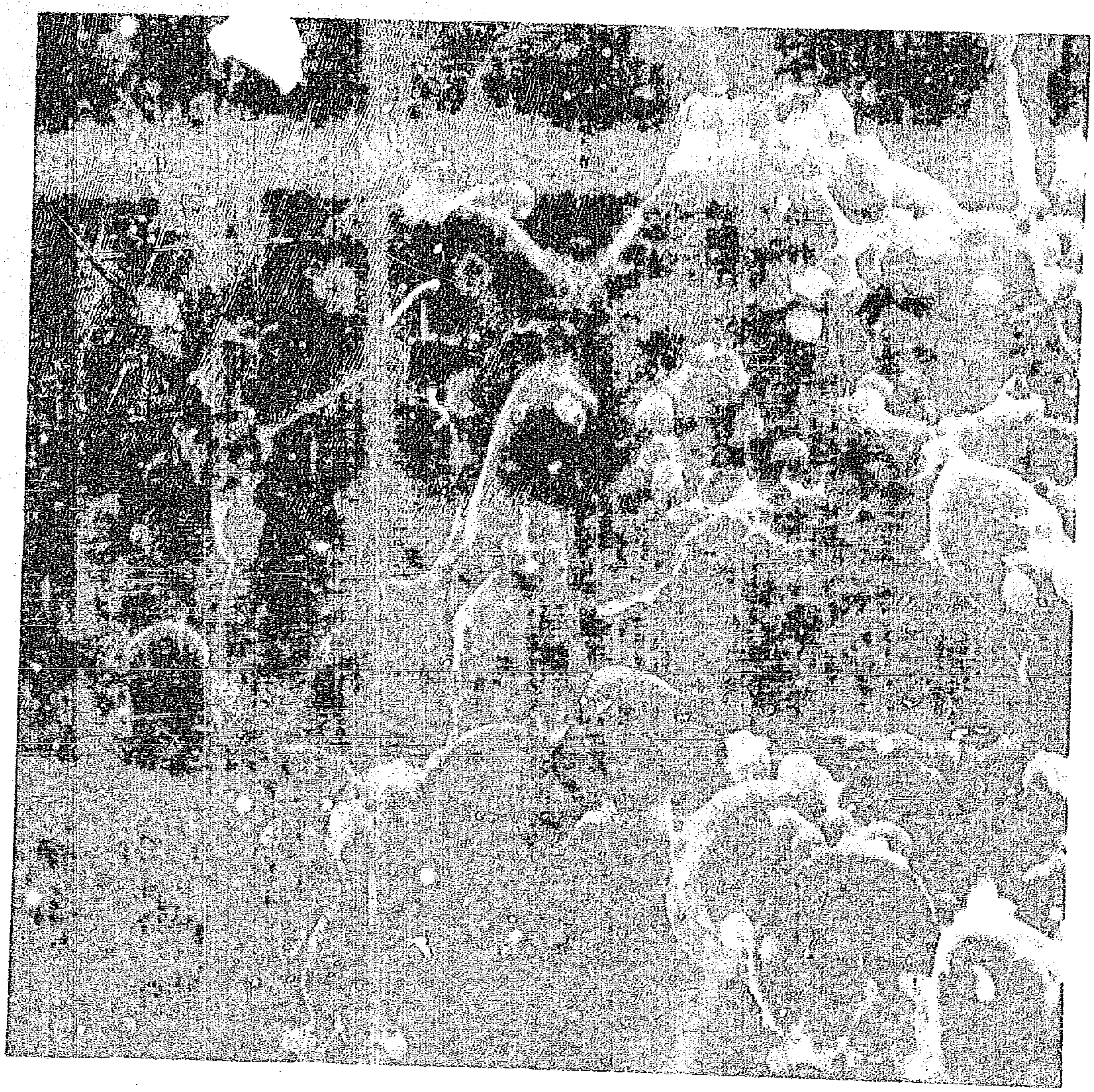

Fig. 2 : S.E.M. of a fractured soft wheat endosperm (from (7)).

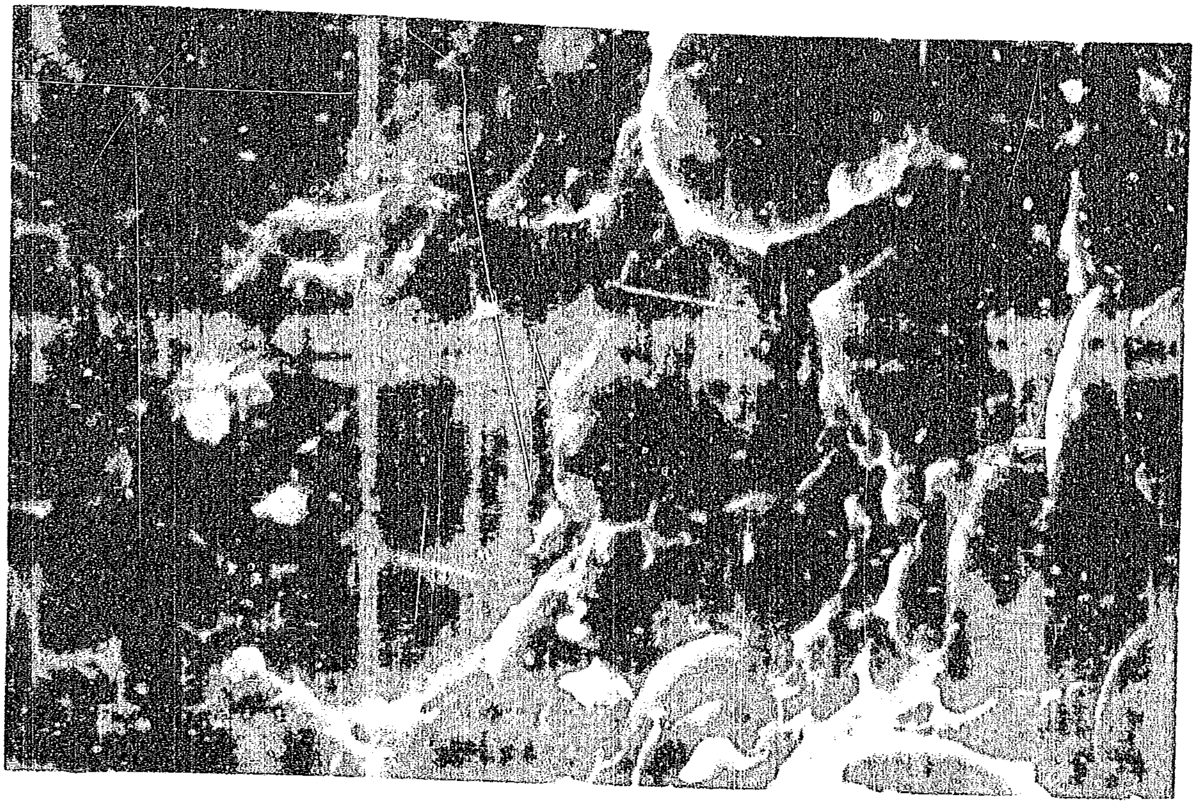

Fig. 3: S.E.M. of a fractured hard wheat endosperm (from (7)).

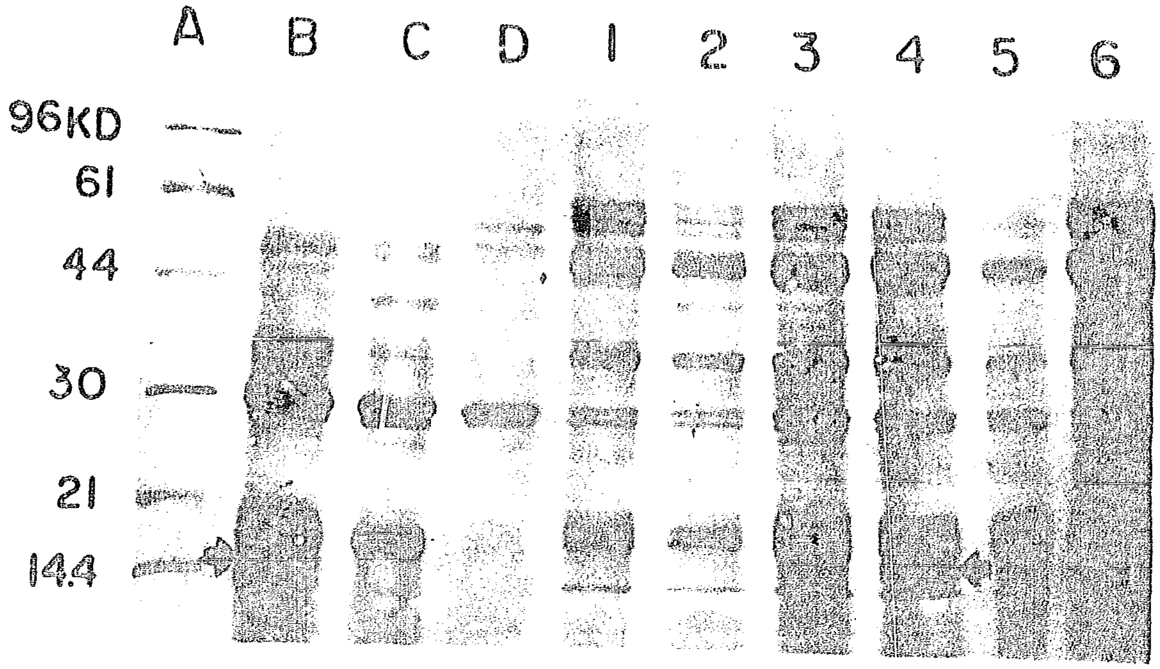

Fig. 4: Gradient gel electrophoresis of starch granule proteins isolated from some Moroccan common wheats:
A- Molecular weight markers, B-Soft wheat, C-Hard wheat, D- Durum wheat, 1-1725, 2- 1711, 3-1724, 4-2306, 5-5/70-9, 6-1710 (from (13)).

(2306) and in the soft wheat standard are shown in Fhg. 4. All the other Moroccan wheats rated hard by PSI, did not contain the band.

Analysis of substitution lines has show that the gene controlling the synthesis of the 15 KD protein is on the short arm of chromosome 5D (GREENWELL and SCHOFIELD, 1986). This chromosome is reported to contain the gene or genes controlling wheat hardness (authors quoted by GREENWELL and SCHOFIELD, 1986) and the free lipids, which correlate well with hardness (MORRISON, 1988). If this protein acts by reducing adhesion between starch granules and endosperm proteins, it may provide the reverse of the hypothesis of SIMMONDS et al (1973) which states the endosperm protein adheres to starch granules via a cementing protein material. However, there is no proof that this protein is the sole factor directly affecting wheat hardness. It could merely be a fortuitous marker for the absence of some other unknown components that do act as the binding agents at the starch-protein interface.

The protein matrix theory

Using genetic studies, SYMES (1969) suggested that the hardness gene affects the type of protein that is laid down within the grain. In addition, GREENAWAY (1969) suggested that proteins were the cohesive agents biding the endosperm particles together, making themresistant to milling.

STENVERT and KINGSWOOD (1977a) reported that results showing equal hardness of starch granules and protein fragments from hard and soft wheats were not enough to invoke an adhesion theory.

They related the difference in hardness to the continuity of the protein matrix and the the strength with which it physiacally entraps starch granules. Therefore, the discontinuity of the protein matrix is the major factor that weaknes endosperm structure. An analogy can be made with graphite and diamond, which are identical in composition but different in structure. The cleavage patterns of soft and hard wheat endosperms, discussed earlier, were used by MOSS et al (1980) to support the protein matrix theory. Two rationales account for the second theory. First, a discontinuous matrix structure would allow the ready release of starch granules as found with soft wheats. Second, the presence of a more ordered structure significantly slowed the rate of moisture penetration, and at one protein level, this difference in structure appeared to reflect the hardness of the grain (STENVERT and KINGSWOOD, 1976,1977b). A strong argument against the protein matrix theory was made by HOSENEY (1987), who pointed out that hard wheats with a discontinuous matrix and soft wheats with a continuous matrix are known.

Electrical Charge Theory

A third theory involving electrostatic repulsion forces between specific proteins has been reported (DOEKES, 1985 quoted by HOSENEY, 1987). The higher (or lower) the forces, the softer (or harder) the wheat will be. Proteins in a dry grain are very unlikely to be involved in such repulsion forces. That is similar to the protein matrix theory. High repulsion forces at the milk stage could lead to a discontinuous protein matrix which, according to both theories, is something that should exist in soft wheats. Flouriness or vitreousness are caused by the presence or absence respectively, of empty spaces in the endosperm. A discontinuity of the protein matrix will lead to an inclusion of empty spaces. Therefore, the protein matrix and electrical charge theories would be ideal to explain flouriness and vitreousness, which, unfortunately, are not necessarily related to wheat hardness.

Genetic control of wheat hardness

All theories discussed above emphasize the importance of proteins being the major chemical agents that determine grain hardness. SYMES (1969) did not find a genetic relationship between hardness and protein content. However, such a genetic relationship may exist, according to BAKER and DYCK (1975). They suggested a possible linkage of genes for nitrogen content with a gene or genes for hardness.

The control of wheat hardness by a major single gene, with modifying minor genes, was suggested by SYMES (1965). He worked with commercial Australian wheats, which are known to have a relatively narrow range of genetic variability. Several other reports have indicated that hardness is controlled by more than one major gene (BEARD and POEHLMAN, 1954, and authors quoted by YAMAZAKI and DONELSON, 1983).

Hardness, Vitreousness and Protein Content Relationships

It is a common belief that highly translucent wheat grains have high protein content. Also schemes that relate protein content to wheat hardness and its appropriate end-use exist (MOSS, 1973). However, wheat hardness has a special biochemical basis that makes it significantly unrelated to vitreousness or protein content which are greatly influenced by environmental conditions (HOSENEY and SEIB, 1973; SIMMONDS, 1974). Several authors have stressed the fact that protein content has essentially no effect on endosperm texture (OBUCHOWSKI and BUSHUK, 1980a ; MILLER et al., 1981a ; MILLER et al., 1982 ; YAMAZAKI and DONELSON, 1983 ; MILLER et al., 1984). Grain translucency is greatly affected by light, temperature, and rate of dessication (PARISH and HALSE, 1968). Weathering can also affect the visual appearance and milling behavior of the grain (MILNER and SHELLENBERGER, 1953). Thus, it is possible to find relatively floury hard wheats and relatively vitreous soft wheats.

For Moroccan wheats Table I summarizes the correlations obtained between hardness (expressed by the Particle Size Index) and vitreousness, protein content, damaged starch, and AWRC. These suggest that any assessment of hardness via protein content and/or vitreousness will be subject to criticism.

Objective methods for hardness testing

There is no standardized objective method to measure wheat hardness. Each method has its peculiar problems inherent to the equipment and measurement principles used. When soft wheats are involved in hard wheat breeding programs, it becomes desirable to have a rapid, simple , and inexpensive test that distinguishes between small samples of hard and soft wheats. It is also preferable to have a test that is insensi.ive ti differences in kernel size, protein content, and normal moisture levels.

Single-kernel testing techniques

1- Indenting: -Leitz Minilsad Hardness Tester

(BARLOW et al, 1973a)

- Barcol Impressor (KATZ et al, 1959)
- Miag Microhardness Tester (SMEETS and CLEVE, 1956 ; GROSH and MILNER, 1959)

Table I : **Correlations of particle size index with protein content, vitreousness, damaged starch, and alkaline water retention capacity of Moroccan wheats. (13).**

Correlated parameters	Sample correlation coefficients(r)	Significant(S) or not (NS) at 95% level	Significant(S) or not (NS) at 99% level
PSI with :			
Proteins	0.07	NS	NS
Vitreousness	-0.49	S	NS
Damaged starch	-0.77	S	S
Alkaline water retention capacity (AWRC)	-0.97	S	S

2- Crushing:

- Instron Universal Testing Machine (IUTM)
- Continuous Automated Single-Kernel hardness Tester: CASK-HAT (LAI et al., 1985 ; LOCKHART et al., 1985)

3- Spectral :

- Laser Light-Scattering Method (GAINES, 1986).
- Near-Infrared reflectance spectroscopy (NORRIS et al ., 1989).

The indenting and crushing devices are all different types of penetrometers that measure the force needed to indent or crush the seeds . Moisture contenent level and uniformity among the grains to be tested are important. In facts, KATZ et al (1961), using the Barcol Impressor, reported that above 13% moisture, hardness decreased rapidly and differences in hardness increased among the kernels. Some of the available instruments are suited for automated testing. For the CASK-HAT apparatus, loading was automated and data collection and interpretation were computerized. This apparatus was claimed to be more than 90% accurate in determining the composition of hard and soft red winter wheats in blends (LAI et al., 1985).

The laser light-scattering method uses the parameter of mean volume diameter (MVD), which represents the particle diameter at cumulative 50% of the volume of the sample particles analyzed (GRAINES, 1986). With this technique, overlappings occured between soft and hard wheat values.

In general, single kernel methods suffer from the effects of kernel weight, size , and density . Also, overlappings occur very often between wheat classes. Consequently, the number of kernels to be tested becomes quite important.

Bulk sample testing techniques

Some of these methods measure grinding resistance, for exemple, the Brabender Hardness Tester, BHT (MILNER and SHELLEN BERGER, 1953 ; GREENAWAY, 1969), and some measure the grinding time (BUTCHER and STENVERT, 1973 ; KOSMOLAC, 1978).There are methods based on seiving and weighing ground or abraded material, as in the pearling index (TAYLOR et al., 1939 ; OBUCHOWSKI and BUSHUK, 1980b) or particle size index, PSI (WORZELLA and CUTLER, 1939 ; MILLER et al., 1984). Spectral methods utilizing near-infrared reflectance (NIR) are also available (WILLIAMS, 1979 ; NORRIS et al., 1989).

Grinding resistance techniques use either the work required to grind the grains (BHT), or the time needed to reach optimum milling performance as a numerical expression of wheat hardness. Work required to grind the grains is insensitive to protein content (10,5 -15,9%), temperature (10 - 20°C), kernel size, and growth location (MILLER et al., 1981a). The BHT test is quite sensitive to moisture content, whereas the grinding-time method is not. STENVERT (1974) found that the effect of moisture was important only when it was about 19% (unlikely to be encountered in practice). Moisture effects were more pronounced for soft wheats than for hard wheats (MILLER et al., 1981b) Grinding time is also unaffected by kernel size (KOSMOLAC, 1978). but is affected by temperature (MILLER et al., 1981b). Damaged starch, flour yield, rheological and breadmaking parameters, and the rate of moisture penetration hardness decreased rapidly and differences in hardness increased among the kernela. Some of the available instruments are suited for automated testing. For the CASK-HAT apparatus, loading was automated and data collection and interpretation were computerized. This apparatus was claimed to be more than 90% accurate in determining the composition of hard and soft red winter wheats in blends (LAI et al., 1985).

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The pearling index was pioneered by TAYLOR et al (1939) using a Barley Pearler. The percentage of the grain pearled away decreased with increasing hardness. The accuracy of the test was increased when dust and powdered material were removed prior to pearling (Mac CLUGGAGE, 1943). Pearling Index values were shown to be affected by both genetic and environmental factors, and did not rank wheat classes in the same order as several other hardness testing techniques. This is supposedly because of the differences in bran properties of wheat cultivars. Pearling procedures used in different laboratories are not exactly the same and show the need for having a standardized procedure (Table II). Moreover, this technique does not seem to complete well with other simple and accurate techniques such as PSI.

Early studies have shown the important effect of wheat meal granulation on baking quality (KRESS, 1929). A granulation number (the parent parameter of the PSI) was used by CUTLER and BRINSON (1935) to distinguish between pastry and bread flours, and was found to be a stable varietal criterion. This was later confirmed by BERG (1947). WORZELLA and CUTLER (1939) were probably the first to define the PSI as it is presently known. Wheat samples were ground and sifted through a nest of sieves. The material passing through the finer sieve (or into the pan) was weighed, expressed in percents of the total, and designated as a PSI. The higher the PSI, the finer the sample, and the softer the wheat.

Many factors affect PSI values. Sprouting affects hard wheats but not soft wheats. Kernel size seems to be more critical with shrunken kernels than with plump grains (POMERANZ and AFEWORK, 1984). In general, an increase in grain moisture content softens wheat grains, increasing PSI values. The data, shown in Table III, do not completely support that theory (MOUJIB, 1988). PSI of most common and durum wheats decreased slightly in an almost linear manner; yet, for some common wheats, PSI values increased when moisture contents increased from 13 to 14,5%. Then later they decreased. Similar data were reported by OBUCHOWSKI and BUSHUK (1980b).

These Results can be explained by the fact that moisture toughens the bran and makes it difficult to pulverize. Moisture also mellows the endosperm, which leads to the production of more fine particles that tend the agglomerate as moisture content increases, partially obstructing sieve openings. Sieve opening diameter influences this phenomenon. Consequently, wheat samples should be kept for several days under conditions of controlled temperature and relative humidity to produce a unifrom moisture content, which should not exceed 14%.

According to the above reports, PSI is a relatively quick, and reliable technique and one of the least costly now available to evaluate wheat hardness. However, as shown by table IV, the lack of complete standardization of the technique is a major drawback, if inter laboratory agreement on an absolute scale is needed.

Table II : **Some examples of Pearling Index procedures**

Sample Size (g)	Moisture	Pearler type	Pearling time (sec)	Screen type	References
20	10-11%	BARLEY PEARLER	180	20-wire	TAYLOR & al. (1939)
20	7-15%	Strong--Scott	70	20-wire	McCLUGGAGE (1943)
20	?	Same	70	?	KELLENBARGER and SWENSON (1948)
?	8-16%	Same	?	20-wire	KRAMER and ALBRECHT (1948)
10	?	Same	120	10-wire	BEARD and POEHLMAN (1954)
10	7-17	Same	60	20-wire	CHESTERFIELD (1971)
20	?	Same	20	?	OBUCHOWSKI and BUSHUK (1980a, b)

Table III : Effect of moisture on the PSI values of moroccan common wheats.

Varieties	Moisture content (%)			
	13 ± 0.3	14.5	15.5	17.0
Tegyey (5/70-9)	35.4	34.0	32.5	29.0
Jouda (1646)	35.8	42.0	37.0	34.0
Nesma (149)	36.5	42.2	39.2	36.0
Baraka (1724)	37.9	33.6	38.4	34.4
Siété-Céros	38.1	40.2	35.8	34.0
Marchouch 9 (Sibara)	38.8	-	-	-
Saba (1710)	39.0	41.6	38.6	38.2
kanz (1712)	39.3	40.8	37.6	36.2
khair (1725)	39.7	40.4	38.8	35.2
1711	41.0	43.6	41.6	38.8
Acsad 67	41.9	44.6	[illegible]	40.8
Marchouch 8 (Marchouch)	42.4	41.4	-	-
Marchouch 10	44.5	34.2	42.8	39.8
Acsad 59	44.4	42.2	41.0	37.8
Tegyey 32 (5/70-32)	47.6	46.4	44.6	42.8
Sais (1615)	54.5	52.5	51.0	47.6
Pinyte (2306)	56.1	52.8	50.5	45.0
Potam	58.4	56.6	52.4	50.4

Table IV : **Some examples of PSI procedures.**

Sample Size (g)	Grinder type	Sieve opening (µm)	Sieving time	References
10	Labconco	85	?	MOSS et al. (1980)
?	Labconco	85	120	SIMMONS et al. (1973)
10	Labconco	75	300	SYMES (1961)
10	Labconco	74	600	WILLIAMS (1967)
20	Brabender	125	420	OBUCHOWSKI and BUSHUK (1980b)
22-23	Falling N. Burr mill	74	600	WILLIAMS and SOBERING (1986b)
15	Labconco	425	30	YAMAZAKI and DONELSON (1983)
10	?	74	600	WILLIAMS (1979)
02	Brabender	106	?	MILLER et al. (1982)

Finally, spectral methods that evalutate hardness of bulk samples are also available . WILLIAMS (1979) reported that wheat hardness and NIR measurements of a ground wheat sample were related. In fact hardness was the most important factor governing variation in the mean particle size (MPS) of wheat samples ground in various types of grinders. MPS markedly affects NIR measurements of proteins and other constituents. Therefore, wheat hardness can be measured by NIR spectroscopy, and, at the same time, other constituents such as protein can be evaluated. Good correlations have been found between MPS and NIR, and the technique has been extensively evaluated for hardness testing (MILLER et al., 1982 ; Mac DONALD 1986 ; WILLIAMS and SOBERING, 1986a). Grinder type markedly affects the MPS/PSI association, and the optimum NIR wavelength may change from one grinding equipment to another (GAINES, 1986). When NIR was compared to PSI and time to grind, correlation was highest between NIR and PSI (MILLER et al ., 1984); however, wheat class

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CONCLUSIONS

Hardness a critical parameter in classifying wheat for commerce, is important throughout the world. It affects the milling behavior of wheat as well as the end-use properties of the flours. The relative hardness or softness has been defined in physical (crushing from, appearance, adhesion, PSI,MPS); chemical (protein as a whole, protein matrix, starch-granule protein); and/or spectroscopic (Laser Light-scattering, NIR) terms. The most common method in use today involves NIR, which is highly correlated to PSI

SUMMARY

Wheat hardness is an important quality trait that affects both milling and baking characteristics. Within common wheats (hexaploid wheats), there are varieties that are soft (soft-milling) and others that are hard (hard-milling). Soft wheats are suited for making cakes, cookies, and pastries. hard wheats are more convenient for bread-making. The knowledge of the biochemical basis of wheat hardness has challenged the scientists for many years. This paper presents a literature review about the theories of wheat hadness, its genetic control, its relationship to other analytical parameters, and the methods of its evaluation.

KEY WORDS : Soft wheat ; Hard wheat ; Hardness.

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