

# Understanding and Modeling the Processing-Mechanical Property Relationship of Bread Crumb Assessed by Indentation

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## ABSTRACT

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Measuring fundamental mechanical parameters such as Young's modulus and critical stress is a straightforward and valid approach to evaluating the physical texture of breadcrumb. The objectives of this study were to evaluate whether such fundamental mechanical properties could be measured by indentation techniques such as the AACC crumb firmness method, and then to alter breadmaking conditions so as to model the relationship between these indentation mechanical properties as a function of crumb moisture content and crumb density. Bread was baked according to a short dough process using Canadian western red spring (CWRS) wheat flour. Factors considered in the design of experi-

ments were proofing time, water absorption, crosshead speed, and indenter diameter. Young's modulus and critical stress, measured with 12- and 20-mm cylindrical indenters, were well covalidated with those obtained from a standard compression test. With increases in proofing time and water absorption, a more porous and compliant bread texture led to decreasing Young's modulus and critical stress. Our results revealed a good mapping of mechanical properties to crumb moisture content and density that were correlated to breadmaking conditions, thus permitting more precise prediction of the mechanical properties that determine bread texture.

As an indicator of freshness and acceptability to consumers, physical texture greatly affects the value of baked products such as bread. Some measurement of mechanical properties is frequently employed for assessing product quality changes resulting from ingredients, processing, and duration of storage (Scanlon et al 2000). On the formulation side, apart from obvious flour-related factors such as the origin and particle size of the flour, the protein or gluten content and the extent of damaged starch in the flour, water (or baking) absorption plays a key role in the production of a high quality bread (Bushuk and Hlynka 1964; Kilborn and Tipples 1982; Pyler 1988). On the processing side, every breadmaking step can have a significant effect on final product quality. However, the visual quality and physical texture of the loaf depend strongly on the proofing conditions (e.g., time, temperature, and relative humidity), the optimization of which is, in turn, determined by formulation and all previous processing steps (Pyler 1988). For instance, proofing a dough beyond its optimal proofing time produces a large and bulky bread loaf with coarse and round crumb grains, while an underproofed bread loaf has low porosity, with small and uneven crumb grains, with the crumb exhibiting high density (Kamman 1970; Zghal et al 1999).

The current method for measuring crumb freshness (firmness) is an indentation technique where a 36-mm diameter cylindrical indenter is pressed into a slice of bread 25.4 mm thick (Approved Method 74-09, AACC 2000). The force recorded at 25% displacement into the sample (6.2 mm) is the measure of bread firmness. Although indentation was originally devised as an empirical technique for evaluating the hardness of metals (Tabor 1951), the conditions under which the mechanical properties of various materials can be extracted from indentation tests have been evaluated (Tabor 1951; Timbers et al 1965). For cellular materials (e.g., breadcrumb) that are subjected to compressive loading, cell wall bending and stretching is responsible for the linear elastic regime, while elastic buckling or plastic collapse is responsible for the nonlinear transformations (Gibson and Ashby 1988; Attenburrow et al 1989). Consequently, the load-displacement curve typically features an initial linear zone immediately followed by a change in slope, so that Young's modulus and critical stress can be extracted from an indentation curve.

Although essentially constant contact area is maintained when a rigid cylindrical indenter penetrates into the sample, the stress within the sample under the probe is not constant, but varies with position under the probe—a minimum at the center and a maximum at the perimeter (Timbers et al 1965). Timbers et al (1965) found that the elastic modulus of potato parenchyma varied with indenter diameter. More recently, Ross and Scanlon (1999) found that the modulus of agar gel measured by indentation was 52% higher than the compressive modulus. This they attributed to a difference between the regions stressed in the two methods: the compressive modulus incorporates the deformation of the pores and solid material as a whole, whereas the indentation modulus is sensitive to the compositional structure that the probe actually encounters. The difference is expected to be particularly striking in cellular solids such as breadcrumb where the porosity is high.

The objectives of this research were twofold: First, because crumb firmness is not an intrinsic mechanical property like elastic modulus and yield stress, we examined the conditions under which Young's modulus and critical stress could be derived from Approved Method 74-09. Second, because understanding and modeling the processing-structure-property relationship is vital to end-product quality, we used indentation to examine and model the effects of breadmaking conditions, such as proofing time and water absorption, on the mechanical properties of white bread crumb.

## MATERIALS AND METHODS

### Breadmaking

Canadian western red spring (CWRS) wheat flour, with a protein content of 12.9%, was used for breadmaking according to a short dough process (Preston et al 1982). All ingredients (Table I) were mixed, using a GRL-200 mixer, at 165 rpm up to 110% past peak at 30°C. The dough was rested for 15 min at 30°C and >85% rh, and then punched and rounded by hand seven times. After 15-min intermediate proof at 30°C and >85% rh, the dough was sheeted by passing successively through a sheeter at a spacing of 8.1, 4.8, and 3.2 mm, and then molded for 30 sec using a GRL molder and panned. Having been proofed for a certain time (the proofing time) at 37.5°C and >85% rh, the panned dough was baked at 204°C for 30 min. All loaves of bread had been cooled at ambient temperature for 25 min before their volumes were measured by rapeseed displacement. Each loaf of bread was sealed in double polyethylene bags and conditioned overnight at ambient temperature to allow for moisture equilibration and bread texture stabilization.

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## Sample Preparation

Just before the test (16–24 hr after baking), the bread loaf to be investigated was removed from its bag and slices ( $\approx 25$  mm thick) were excised from the central portion of the loaf (Zghal et al 2001) using a serrated bread knife and digital calipers. Gentle and even hand movement was applied to minimize spoiling crumb texture. All slicing for one loaf was completed within 5 min. The slices of each loaf were immediately sealed in a zipped polyethylene bag. Just before testing, a slice was removed and trimmed into a rectangle with long dimensions of  $\approx 50$  mm  $\times$  50 mm for indentation testing, or into a cylinder using a 30 mm-diameter sharp stainless steel borer for compression testing. Three replicates were used for all measurements. Sample dimensions (thickness, length, width or diameter) were measured using the calipers at four spots uniformly distributed along each dimension. The sample was weighed on a digital balance immediately before and after the test. The average of these two values, divided by the sample volume, gave the crumb density ( $\rho$ ) in g/cm<sup>3</sup>. The tested sample as a whole was weighed after drying in an air-circulated oven at 105°C for  $\approx 40$  hr to determine its moisture content (MC, wt%) (Fontanet et al 1997).

## Indentation and Compression Tests

Indentation and compression tests were performed on a computerized Lloyd testing machine (model L1000R) at ambient conditions ( $23 \pm 2^\circ\text{C}$ , ambient humidity). The 100 N capacity load cell was calibrated with standard weights before each day's testing. Correlation between the force readings and the standard weights were linearly fitted. All measurements were corrected using the derived function. Cylindrical indenters with various diameters and an aluminum bottom platen were used for indentation, whereas two aluminum platens to which Teflon sheets were glued were used for compression. Compressive Young's modulus ( $E$ ) and critical stress ( $\sigma_c$ ) were extracted from engineering stress-strain curves (Attenburrow et al 1989). From indentation load-displacement curves,  $E$  and  $\sigma_c$  were calculated by

$$E = \alpha(1 - \nu^2)/D \quad (1)$$

$$\sigma_c = 4P_c/\pi D^2 \quad (2)$$

where  $\alpha$  denotes the slope of the linear elastic regime in a load-displacement curve;  $D$  the indenter diameter,  $\nu$  the Poisson's ratio,

**TABLE I**  
Formulation for Canadian Short Process Baking Test

Ingredients	Mass (g)
Flour (14% moisture basis)	200
Yeast (compressed)	6.4
Salt (noniodized)	4.8
Sugar	8
Whey	8
Shortening	6
Malt syrup	0.4
Ammonium phosphate	0.2
Ascorbic acid	0.015
Water (distilled)	variable <sup>a</sup>

<sup>a</sup> Depending on the moisture content of the flour and the water absorption required.

**TABLE III**  
Effects of Proofing Time ( $t$ ), Water Absorption ( $w_a$ ), and Indenter Diameter ( $D$ ) on Least Square Means for Young's Modulus ( $E$ ) and Critical Stress ( $\sigma_c$ )

$t$ (min)	$E$ (Pa)	$\sigma_c$ (Pa)	$w_a$ (%)	$E$ (Pa)	$\sigma_c$ (Pa)	$D$ (mm)	$E$ (Pa)	$\sigma_c$ (Pa)
45	52,881	6,459	47.5	91,339	11,112	4	...	...
70	44,117	4,916a <sup>a</sup>	53.5	25,865	2,970	12	39,692	5,508b
90	35,234	4,323a	61.3	15,027	1,616	20	48,462	4,957b

<sup>a</sup> Values followed by the same letter are not significantly different ( $P < 0.05$ ).

taken as 0.21 for bread crumb (Rohm et al 1997), and  $P_c$  the critical load.

## Experimental Designs

We planned our experiments by multilevel factorial design. Factors considered in our first data set (99 runs in total) were proofing time ( $t$ : 35, 45, 70, 85, 90 min) and water absorption ( $w_a$ : 47.5, 53.5, 61.3, 65.0%) on the processing side, and crosshead speed (5, 100, 200 mm/min) and indenter diameter ( $D$ : 8, 12, 20 mm) on the testing side. All design, analysis of variance (ANOVA), and nonlinear regression were made using Statgraphics Plus v5.0 software (Manugistics Inc., Rockville, MD). Comparison of least square means (LSM) for the property of interest was performed in ANOVA of the results for the first data set. In a balanced design, LSM are equal to the arithmetic average, whereas in an unbalanced design they are not (Hoaglin et al 1991). Default confidence interval for the unbalanced LSM used was 95.0%. Using LSM permitted the effect of a factor to be evaluated while averaging out effects of the rest.

Based on the ANOVA results of the first set of experiments, the experimental design was refined to allow the experiments to be more compact and economical while retaining the vital effects of interest. In the second set of experiments, those components that contributed little to the variability of both Young's modulus and critical stress were dropped. To retain a three-level design for all factors, a 4-mm diameter indenter was substituted for the 8-mm one. In the redesigned experiments, the proofing times were 45, 70, and 90 min, water absorption 47.5, 53.5, and 61.3%, and indenter diameters 4, 12, and 20 mm. Three replicates were run for each treatment. For conciseness, ANOVA tables are not presented here.

For validation of models developed for the effect of processing on crumb texture, extra loaves were baked using a set of proofing time of 61 min and a water absorption of 47.5% (excluded from the baking conditions used for deriving the models), and a new set of 70 min and 61.3% loaves.

## RESULTS AND DISCUSSION

### Effect of Crosshead Speed

For viscoelastic materials such as bread crumb, strain rate is a factor affecting the measured mechanical parameters (Hibberd and Parker 1985). A lower strain rate allows more relaxation and plastic flow, which is apparent as a difference in the load-displacement relationship (Munoz et al 1986; Emilia Rosa and Fortes 1988). However, ANOVA of our first data set revealed that

**TABLE II**  
Assessing Prediction Accuracy for Breadcrumb Density ( $\rho$ )<sup>a</sup>

$t$ (min)	$w_a$ (%)	$[t]$	$[w_a]$	$\rho$ (g/cm <sup>3</sup> )	
				Measured <sup>b</sup>	Predicted <sup>c,d</sup>
61	47.5	0.47	0.00	0.209	0.189
70	61.3	0.64	0.79	0.123	0.128

<sup>a</sup>  $t$  = proofing time;  $[t]$  = normalized proofing time;  $w_a$  = water absorption;  $[w_a]$  = normalized water absorption.

<sup>b</sup> Standard error for measured density  $< 0.002$ .

<sup>c</sup>  $\rho = 0.223 - 0.072 \cdot [t] - 0.062 \cdot [w_a]$ .

<sup>d</sup> Standard error of estimation = 0.02.

indenter speed hardly affected Young's modulus ( $P = 0.28$ ), although it did contribute significantly to the variability of critical stress ( $P = 0.02$ ). Therefore, the crosshead speed was fixed at 100 mm/min in the second set of experiments. Assessments of crosshead speed on crumb firmness have previously shown it to be a factor contributing to higher force values (Baker et al 1986a,b), but it was not deemed to be a "critical factor" (Baker et al 1986a).

### Effect of Indenter Size

The AACC firmness test (Approved Method 74-09) does have the potential for measuring fundamental mechanical properties of the bread crumb, such as Young's modulus (Sneddon 1965) and critical stress (Andrews et al 2001) using Equations 1 and 2, respectively. Because size effects in indentation of cellular solids can impede extraction of true mechanical properties, it is essential to covalidate measurements obtained from indentation with those from compression (Ross and Scanlon 1999). When using the 12- and 20-mm indenters, the indentation Young's modulus could be readily equated with the compressive modulus (Fig. 1A). Likewise, for these two indenters, the indentation critical stress was linearly proportional ( $R^2 = 0.954$ ) to the compressive critical stress (Fig. 1B). Interestingly, if the critical stress of breadcrumb is associated with plastic collapse of the cell walls, the slope value of 1.8 in Fig. 1B places bread crumb in between a classical cellular solid, where the ratio of indentation critical stress to compressive critical stress should be 1.0 (Gibson and Ashby 1988), and a rigid-perfectly plastic noncellular solid, where the ratio should be  $\approx 3.0$  (Tabor 1951; Miller 2000). However, for the 4-mm indenter, large deviation was observed for both mechanical parameters between the two methods. This indicated that an indenter of this size was too small to obtain valid bulk properties of bread crumb, likely arising from the small ratio of indenter diameter to crumb cell size (Andrews et al 2001). From digital image analysis results (Zghal et al 1999), the average diameter of crumb grain cells (CWRS bread baked at  $w_a$  of 60.0–65.0%) was  $\approx 0.8$  mm. Therefore, according to the indentation criteria evaluated by Andrews et al (2001), indenter diameter should be  $>5.6$  mm if the breadcrumb is to be regarded as a continuum so that indentation measurements can be assigned as bulk properties of the bread crumb. The specified dimensions for Approved Method 74-09 infer that valid measurements of Young's modulus and critical stress will be obtained for all but the most open of breadcrumb types, but evidently not for the 4-mm indenter.

### Effect of Processing on Crumb Density and Moisture

A larger loaf of bread is attainable by increasing either proofing time or water absorption during breadmaking, although optimal conditions are normally specific to given dough development and baking processes (Skeggs and Kingswood 1981; Pylar 1988). Because loaf volume is negatively correlated to breadcrumb density (Zghal et al 1999), the effect of processing on crumb density, rather than loaf volume, will be discussed due to the causal relationship between crumb properties and density which arises from the cellular structure of the crumb (Scanlon and Zghal 2001). A response surface based on regression (of the first data set) using general linear models of the effects of normalized proofing time ( $[t]$ ) and normalized water absorption ( $[w_a]$ ) on crumb density is shown in Fig. 2. Normalization of a variable was based on the span investigated, i.e., (variable-minimum)/(maximum-minimum). Using the normalized values instead of the measured ones minimizes floating errors during regression computing, especially when a big discrepancy exists between variable spans. Crumb

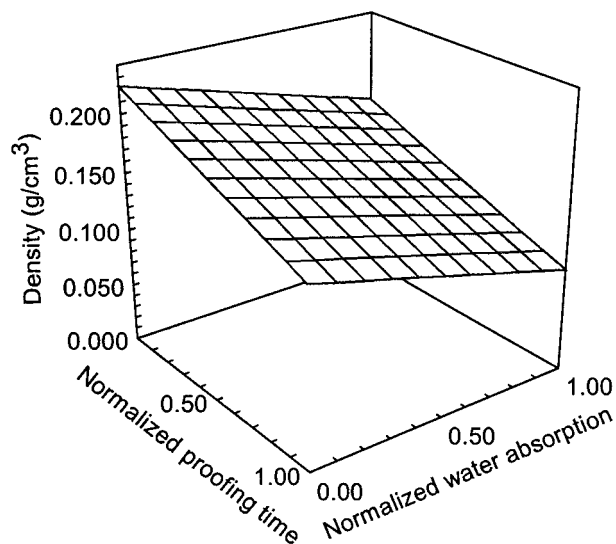


Fig. 2. Response surface of density vs. normalized proofing time and water absorption.

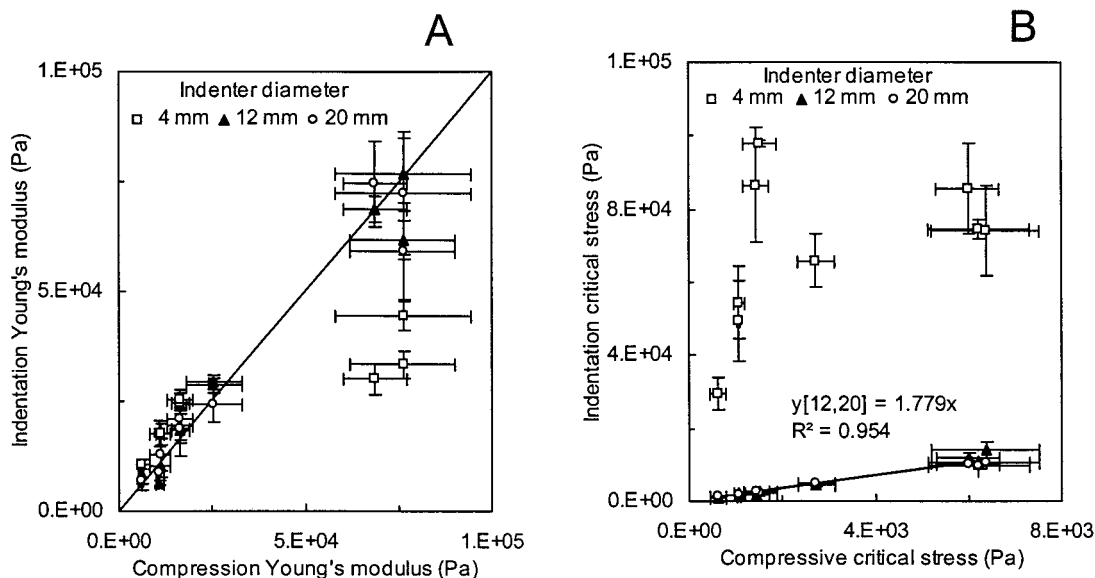


Fig. 1. Covalidation of Young's modulus (A) and critical stress (B) measured by compression and indentation.

density decreased as both  $[t]$  and  $[w_a]$  increased. The derived model is expressed as

$$\rho = 0.223 - 0.072 \cdot [t] - 0.062 \cdot [w_a] \quad (3)$$

The  $R^2$  value is 0.717. To confirm the model, it was used to predict crumb density for the validation set (Table II). Prediction accuracy was good for bread made under optimal conditions but not for the low water absorption dough.

Examining the effect of breadmaking conditions on crumb moisture content is pertinent because greater moisture content would increase crumb density, and therefore be expected to increase values of many of its mechanical properties (Gibson and Ashby 1988), including consumer evaluation of crumb freshness (Ponte and Ovadia 1996). However, moisture serves as a plasticizer for the crumb cell wall materials and this will tend to depress measured mechanical parameters (Liu 1998). According to multiple-variable analysis of proofing time ( $t$ ), water absorption ( $w_a$ ) and the moisture content of the bread crumb ( $MC_c$ ), proofing time was not statistically correlated to  $MC_c$ , despite the freer diffusion path for moisture in the more open-celled doughs proofed for longer times. As expected,  $MC_c$  was highly correlated ( $R^2 = 0.983$ ) to  $w_a$  ( $P = 0$ ). Linear fitting of  $MC_c$  versus  $w_a$  gave

$$MC_c = 0.44 \cdot w_a + 13.9 \quad (4)$$

The  $R^2$  value is 0.997, while the intercept (13.9%) was almost the same as the flour moisture basis (14.0%).

### Predicting Crumb Texture from Processing Conditions

Table III (based on the redesigned experiments) presents the LSM for  $E$  and  $\sigma_c$ , contributed by  $t$ ,  $w_a$ , and the two valid  $D$ . Basically, increasing both  $t$  and  $w_a$  reduced both  $E$  and  $\sigma_c$ , which infers

a more compliant and weaker bread texture related to a low-density loaf. Although indenter size effects were not observed for measurement of the mechanical properties in Fig. 1, when averaged over all processing treatments for the second data set, Young's modulus was significantly larger for the larger indenter, although critical stress was not.

Because breadcrumb is a hydrated cellular material, and as noted above, density and moisture would be expected to confound the effect of one another, it was useful to map both moisture content and density to the mechanical properties of the bread crumb. Regressions were run on the second data set using the same protocol for both mechanical properties

$$P = a_1 \cdot [MC_c]^2 + a_2 \cdot [\rho]^2 + a_3 \cdot [MC_c] \cdot [\rho] + a_4 \cdot [MC_c] + a_5 \cdot [\rho] + a_6 \quad (5)$$

where  $P$  denotes the property of interest (i.e.,  $E$  and  $\sigma_c$  here),  $a_i$  ( $i = 1, 2, \dots, 6$ ) is the parameter to be estimated, and  $[MC_c]$  and  $[\rho]$  are the normalized moisture content and normalized density of breadcrumb, respectively. Assigning  $P$  as a quadratic function of  $[\rho]$  was inspired by the findings of Gibson and Ashby (1988) and Attenburrow et al (1989); the  $[MC_c]$  part was based on previous observations (Liu 1998).

The resulting regressions all had high  $R^2$  values (0.90–0.97). Generally speaking, increasing moisture content (by manipulation of water absorption) and decreasing density (by manipulating proof time) led to a decrease in both Young's modulus and critical stress measured by the 12- and 20-mm indenters, although the effect was more pronounced for Young's modulus (Fig. 3). The size effect on Young's modulus between 12 and 20-mm indenters almost disappeared in the regime of high moisture content or density (Fig. 3A), while the effect was negligible for critical stress

TABLE IV  
Predicted Young's Modulus ( $E_p$ ) and Critical Stress ( $\sigma_{cp}$ ) Compared with Experimental Values Measured by 12-mm Diameter Indenter<sup>a</sup>

$t$ (min)	$w_a$ (%)	$MC_c$ (%) <sup>b</sup>	$\rho$ (g/cm <sup>3</sup> )	$[MC_c]$	$[\rho]$	$E$ (Pa)	$E_p$ (Pa) <sup>c</sup>	$\sigma_c$ (Pa)	$\sigma_{cp}$ (Pa) <sup>d</sup>
35	53.5	37.5	0.200	0.49	0.70	45,310	42,256	5,597	5,434
35	53.5	37.5	0.199	0.49	0.69	51,571	41,941	5,367	5,362
70	65.0	42.5	0.115	1.18	0.09	19,381	14,658	1,972	2,331
70	65.0	42.5	0.117	1.18	0.11	17,445	15,032	2,308	2,335
90	65.0	42.5	0.086	1.18	-0.11	8,229	9,124	1,203 <sup>e</sup>	2,716 <sup>e</sup>
90	65.0	42.5	0.117	1.18	0.11	7,265	15,032	1,141 <sup>e</sup>	2,335 <sup>e</sup>

<sup>a</sup>  $t$  = proofing time;  $w_a$  = water absorption;  $MC_c$  = moisture content;  $[MC_c]$  = normalized moisture content;  $\rho$  = density;  $[\rho]$  = normalized density;  $E$  = Young's modulus;  $\sigma_c$  = critical stress.

<sup>b</sup>  $MC_c = 0.44 \cdot w_a + 13.9$ .

<sup>c</sup>  $E_p = 71,210.1 [MC_c]^2 - 2,321.44 [\rho]^2 - 30,092.0 [MC_c] \cdot [\rho] - 115,783.0 [MC_c] + 62,381.8 [\rho] + 49,643.5$ .

<sup>d</sup>  $\sigma_{cp} = 14,977.7 [MC_c]^2 + 9,662.1 [\rho]^2 + 2,051.99 [MC_c] \cdot [\rho] - 25,700.6 [MC_c] - 4,087.98 [\rho] + 11,869.0$ .

<sup>e</sup> Statistically different values between predicted and experimental parameter ( $P < 0.05$ ).

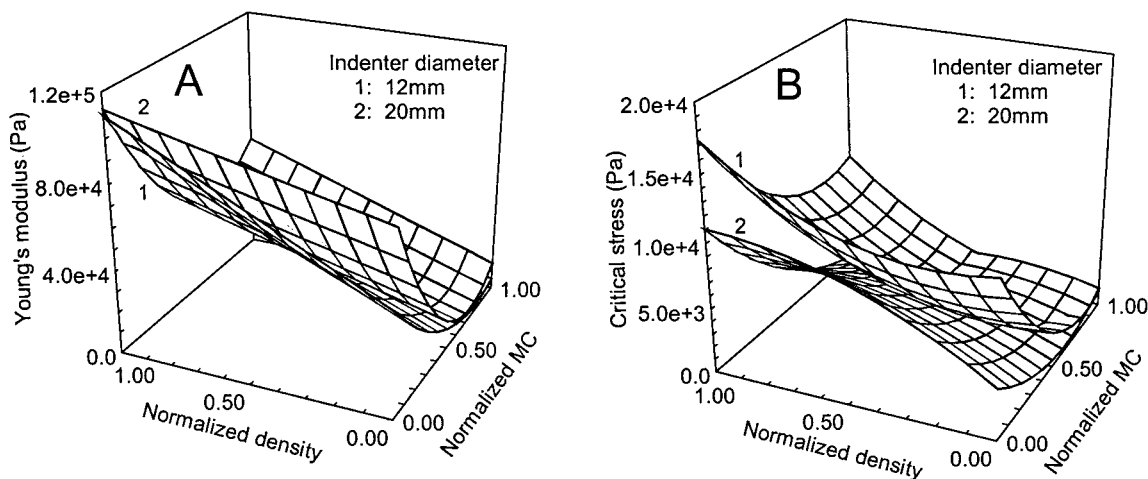


Fig. 3. Response surface of Young's modulus (A) and critical stress (B) vs. normalized moisture content (MC) and density.

(Fig. 3B). A striking plasticizing effect induced by excessive water ( $\leq 41.0\%$  in the wall materials) may account for the indenter size effect diminishing in the high moisture content regime. In the high density regime, low porosity and finer cell size allowed the cellular solid to behave more like a compact and dense material. Therefore, an effect of indenter size on measured parameters diminished at smaller crumb cell sizes (Miller 2000).

Table IV compares the experimental data extracted from the preliminary investigations against the predictions derived from Equation 5 for the 12-mm indenter. Due to lack of moisture content measurements in the preliminary investigations, the moisture content values presented in the table were estimated according to Equation 4. The predictions were consistent with measurements for both  $E$  and  $\sigma_c$ , even when  $[MC_c]$  and  $[\rho]$  were out of the tested range (e.g.,  $[MC_c] = 1.18$ ;  $[\rho] = -0.11$ ) used for constructing the model. ANOVA showed no statistically significant differences between any LSM pair of the measured and predicted values within a 95.0% confidence interval, except for critical stress in the last case ( $t = 90$  min,  $w_a = 65.0\%$ ).

## CONCLUSIONS

Accurate measurement of the Young's modulus of breadcrumb was feasible from indentation measurements. Accurate determination of critical stress from indentation is also possible if more research is performed to assign a reliable value for the constraint factor associated with indentation of the bread crumb. Indenter diameter should be  $\geq 12$  mm. Mapping Young's modulus and critical stress to crumb moisture content and density, altered according to breadmaking conditions, was an innovative and effective way of modeling the processing-property relationship for bread.

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