Effects of hydrocolloids as texture improver in coriander bread

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Abstract An attempt was made to study the effects of hydrocolloids on loaf weight, volume, crumb grain characteristics, crumb moisture, firmness and dough rheological properties on 3.0 % coriander leaf supplemented breads. Carrageenan (CA), carboxymethylcellulose (CMC), guar gum (GG) and xanthan gum (XG) were added in the proportions of 0.25, 0.5, 0.75 and 1.0 % w/w of 100 g wheat flour. Addition of hydrocolloid increased the loaf volume and decreased the average cell area. An inverse relationship was observed between specific volume and average cell area. XG showed uniform change in crumb moisture on storage at all levels of substitution. However highest loss of moisture occurred in bread samples supplemented with GG. Crumb firming kinetics using Avrami's model showed slower firming rates for GG and CMC. High complex modulus (G^*) values were observed in breads with 0.75 and 1.0 % XG.

Keywords Hydrocolloid · Coriander bread · Crumb grain characteristics · Avrami model · Rheology

Introduction

Bread is a widely consumed product worldwide and wheat bread is the most popular. In recent years hydrocolloids have gained much attention as bread improvers due to their effect regarding dough function ability, quality characteristics and product preservation (Collar et al. 1999; Leon et al. 2000; Rosell et al. 2001; Linlaud et al. 2011). Hydrocolloids have the ability to increase water retention and increasing intermolecular viscosity thereby allowing entrapment of more gas in the start-protein matrix. At lower level of incorporation (< 1 %), hydrocolloids improve the quality of baked goods

(Onweluzo et al. 1999), increase water retention and decrease firmness and starch retrogradation (Collar et al. 1999).

The most well know and applied hydrocolloids in the industry include alginates, carrageenans, agar, guar gum, arabic gum and carboxymethyl cellulose (Gómez-Díaz and Navaza 2003). Mettler and Seible (1993) and Shittu et al. (2009) used carboxymethylcellulose, guar gum and xanthan on rye bread and cassava bread recipes respectively to improve their quality and extend the shelf life. Hydroxypropylmethylcellulose has been used in many studies as anti-staling agents and improvers to yield higher specific volume, softer crumb and better sensory characteristics (Rosell et al. 2001; Yaseen et al. 2001). Addition of hydrocolloids namely sodium alginate, k-carrageenan, xanthan gum and hydroxypropylmethylcellulose (HPMC) improved wheat dough stability during proofing (Rosell et al. 2001). Collar et al. (2001) studied the effect of CMC and HPMC addition on dough and bread performance of formulated wheat breads. Hydrocolloids can also be used in combinations or with other additives to effect synergistically on their functional properties (Bollain and Collar 2004; Peressini et al. 2011). Several gums i.e. xanthan, guar gum, locust bean gum, gum arabic can also induce dough strengthening, improve crumb grain and texture of the final bread (Guarda et al. 2004; Rodge et al. 2012).

Until now, very little work has been done on the use of hydrocolloids in composite flour breads. Though substitution of wheat flour with other flours give acceptable composite bread loaf, this may lead to reduced bread quality due to the lowered gluten content reducing the gas retention capacity. The aim of the present study was to investigate the effects of some well known hydrocolloids i.e. carrageenan, carboxymethylcellulose, guar and xanthan gum on the quality of the coriander leaf fortified bread (Das et al. 2012). The objectives of the study aims at i) evaluating the effects of the hydrocolloids on bread loaf weight, volume and crumb grain characteristics, ii) examining the staling properties (crumb moisture and firmness) of the bread samples by applying Avrami's non-linear regression equation in studying the bread crumb firming kinetics and iii) understanding the effect of hydrocolloids on rheological properties of bread dough and their mathematical modeling.

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Materials and methods

Materials

Commercial bread-making wheat flour (moisture 13.2 ± 0.45 %, ash 0.5 ± 0.25 %, dry gluten 10.62 ± 0.98 %, protein 11.15 ± 0.62 %, fat 1.85 ± 0.12 % and carbohydrate 61.68 %), sugar, refined oil and salt were purchased from the local stores of Jadavpur, Kolkata, India. Compressed Baker's yeast (Saf Yeast Company Pvt. Ltd., Mumbai, India) was used in the fermentation of bread. Glycerol monostearate (Loba Chemie Pvt. Ltd., Mumbai, India) was used in the bread formulation. Fresh coriander leaves were bought from the local vegetable market of Kolkata. Carrageenan and carboxymethylcellulose were purchased from Merck Specialities Pvt. Ltd., Mumbai, India and guar gum, xanthan gum, from Himedia Laboratories Pvt. Ltd. (Mumbai, India).

Preparation of coriander leaf powder

Coriander leaves were cleaned and washed in tap water to remove the adhering dirt. They were then blanched at 50 °C for 30 s. and then dried in a tray dryer (ICT, Kolkata, India) at 50 °C for 3 h. The dried leaves were then ground in a common grinder (Prestige Stylo Mixer Grinder, Prestige, India) to obtain the coriander leaf powder and sifted to less than 150 μ m particle size (BSS 100). The coriander leaf powder obtained had a moisture content of 8.17 ± 0.38 % and ash content of 87.11 ± 0.84 % (AACC 2000).

Preparation of bread

The bread recipe consisted of compressed yeast 2.5 %, sugar 5.0 %, salt 2.0 %, refined oil 5.0 %, glycerol monostearate 1.5 % and water 60.0 %. Yeast was dissolved in warm water (10 ml at 37 °C) and kept for 15 min for activation of the yeast cells. Approximately 1 g of each flour and sugar were used as feed for yeast. Mixing is an important step for achieving homogenous and soft dough. Here, mixing was carried out manually according to the straight dough method. The dry ingredients, refined oil and the activated yeast were taken in a bowl; a fixed amount of water (60 ml) was added slowly which was accompanied by kneading for approximately 10 min. The required consistency of the dough samples were checked by the physical handling of the samples.

The primary properties considered in this respect were the stickiness of the dough samples to the container and hands, the tearing of the dough samples when a small part of it is stretched and the springiness of the dough samples when a small part is mildly deformed. The dough was then rounded and kept in a bowl for the first proofing at room temperature for about 40 min. A wet cloth was covered over the bowl to maintain a relative humidity of 80–90 %. After the first proofing, the dough was punched and worked up lightly so that the excess CO_2 gas could escape out and the gas cells were redistributed in size and space. The dough was then shaped to fit lightly in greased bread molds, and kept for final proofing for about 1 h at 40 ± 1 °C. Finally, after second proofing, the breads in molds were baked in rotary oven (CM HS108, Chanmag Bakery Machine Co. Ltd., Taiwan) at 220 ± 2 °C for 18–20 min. The prepared bread samples were cooled for about 1 h at room temperature and subsequently analyzed for its relevant physical and chemical properties.

Coriander-wheat flour breads were prepared by mixing 100 g wheat flour with 3.0 % w/w of coriander leaf powder. Hydrocolloids were added each at four different concentrations of 0.25, 0.50, 0.75 and 1.0 % on 100 g flour basis. All bread formulations studied in this work and their codes are summarized in Table 1

Bread analyses

Loaf size

The loaves were weighed immediately after removal from the baking oven. The loaf volumes of the bread samples were measured by the seed displacement method in ml (Sahin and Summu 2006) taking a known volume of 700 ml. Specific loaf volumes were calculated by dividing the loaf volume by the loaf weight, and expressed in ml/g.

Crumb moisture

Bread crumb moisture content was determined by taking about 2 ± 1 g of the bread crumb in small aluminium containers and drying for 2 h at 130 ± 2 °C in a hot air oven (Reliance Enterprise, Kolkata, India) (AACC 2000). After drying, the samples were cooled in desiccators. Moisture content was determined as follows:

$$\% \text{ moisture content} = \frac{\text{initial wt. of the sample} - \text{final wt. of the sample}}{\text{initial wt. of the sample}} \times 100 \quad (1)$$

Crumb firmness

Firmness of the bread samples were measured with Instron Universal Testing Machine, Table Model 4301 (Instron Ltd.,

High Wycombe, Bucks, UK) in the compression mode fitted with a 100 N load cell. The bread samples were sliced and the middle slices having a height of 25 mm, when placed horizontally under a flat plate probe were taken for measurement.

Table 1 Effect of different hydrocolloids in different proportions on the physical properties of bread with 3 % coriander leaf powder

Hydrocolloids	Levels of hydrocolloids (g/100 g)*	Sample code	Loaf weight (g)	Loaf volume (ml)	Specific loaf vol. (ml/g)	Total cells	Total cell area (mm ²)	Average cell size (mm ²)	Total cell to total area (%)	Ratio of cells $\leq$ 2 mm ² to cells $\leq$ 10 mm ² (%)
–	–	CON	151.2 $\pm$ 0.13 ^a	465.9 $\pm$ 1.12 ^m	3.08 $\pm$ 0.007 ^c	880 $\pm$ 16.8 ^c	30,101 $\pm$ 486.7 ^a	34.21 $\pm$ 1.17 ⁱ	33 $\pm$ 0.5 ^u	72 $\pm$ 0.4 ^k
–	–	COR	152.0 $\pm$ 0.22 ^a	354.2 $\pm$ 0.96 ⁿ	2.33 $\pm$ 0.009 ^f	845 $\pm$ 75.1 ^c	40,370 $\pm$ 326.6 ^b	48.08 $\pm$ 4.89 ^j	45 $\pm$ 0.4 ^u	71 $\pm$ 1.1 ^k
Carrageenan	0.25	CA1	157.7 $\pm$ 0.5 ^b	478.5 $\pm$ 0.76 ^o	3.04 $\pm$ 0.013 ^g	1268 $\pm$ 14.8 ^d	29,075 $\pm$ 469.3 ^c	22.93 $\pm$ 0.55 ^k	32 $\pm$ 0.5 ^v	71 $\pm$ 0.3 ^k
Carrageenan	0.5	CA2	156.0 $\pm$ 0.43 ^c	442.4 $\pm$ 0.52 ^p	2.84 $\pm$ 0.009 ^h	1195 $\pm$ 25.5 ^e	36,890 $\pm$ 576.7 ^{ab}	30.87 $\pm$ 1.01 ^l	41 $\pm$ 0.6 ^w	71 $\pm$ 0.9 ^k
Carrageenan	0.75	CA3	153.9 $\pm$ 0.96 ^d	443.8 $\pm$ 1.12 ^q	2.88 $\pm$ 0.011 ⁱ	1319 $\pm$ 35.1 ^f	35,598 $\pm$ 270.8 ^{bc}	26.99 $\pm$ 0.66 ^m	40 $\pm$ 0.3 ^x	73 $\pm$ 1.3 ^k
Carrageenan	1	CA4	156.0 $\pm$ 0.28 ^e	418.0 $\pm$ 0.76 ^r	2.68 $\pm$ 0.009 ^j	1225 $\pm$ 12.4 ^g	34,852 $\pm$ 115.6 ^d	28.46 $\pm$ 0.20 ⁿ	39 $\pm$ 0.1 ^y	72 $\pm$ 1.2 ^l
Carboxymethyl-cellulose	0.25	CMC1	146.8 $\pm$ 0.75 ^f	475.6 $\pm$ 1.11 ^s	3.24 $\pm$ 0.024 ^{ef}	1334 $\pm$ 34.6 ^h	34,261 $\pm$ 413.0 ^e	25.68 $\pm$ 0.43 ^o	38 $\pm$ 0.5 ^z	70 $\pm$ 0.6 ^m
Carboxymethyl-cellulose	0.5	CMC2	153.1 $\pm$ 0.22 ^g	460.7 $\pm$ 0.79 ^t	3.01 $\pm$ 0.008 ^k	1136 $\pm$ 14.3 ⁱ	38,394 $\pm$ 511.8 ^{ad}	33.81 $\pm$ 0.88 ⁱ	43 $\pm$ 0.6 ^{xy}	75 $\pm$ 0.8 ⁿ
Carboxymethyl-cellulose	0.75	CMC3	154.5 $\pm$ 1.03 ^h	451.5 $\pm$ 0.54 ^{nm}	2.92 $\pm$ 0.022 ^l	1123 $\pm$ 8.1 ^j	35,936 $\pm$ 164.0 ^{ae}	34.30 $\pm$ 0.11 ⁱ	40 $\pm$ 0.2 ^{uv}	71 $\pm$ 0.4 ^k
Carboxymethyl-cellulose	1	CMC4	150.8 $\pm$ 0.58 ^a	423.1 $\pm$ 0.67 ^{op}	2.81 $\pm$ 0.009 ^m	1234 $\pm$ 35.1 ^k	32,660 $\pm$ 456.3 ^f	27.58 $\pm$ 0.42 ^{pq}	36 $\pm$ 0.3 ^{yz}	69 $\pm$ 0.7 ⁿ
Guar gum	0.25	GG1	156.6 $\pm$ 0.43 ⁱ	450.9 $\pm$ 0.75 ^{pq}	2.88 $\pm$ 0.008 ⁿ	1199 $\pm$ 35.3 ^{ij}	36,470 $\pm$ 554.4 ^g	30.44 $\pm$ 1.38 ^{op}	41 $\pm$ 0.6 ^{wx}	73 $\pm$ 0.9 ^k
Guar gum	0.5	GG2	157.0 $\pm$ 0.36 ^j	449.9 $\pm$ 0.45 ^{rs}	2.87 $\pm$ 0.006 ^{mn}	1429 $\pm$ 12.7 ^l	31,059 $\pm$ 86.7 ^h	31.60 $\pm$ 0.49 ^q	35 $\pm$ 0.1 ^s	63 $\pm$ 1.1 ^o
Guar gum	0.75	GG3	154.5 $\pm$ 0.75 ^k	460.7 $\pm$ 1.37 ^u	2.98 $\pm$ 0.007 ^{kl}	1065 $\pm$ 18.6 ^m	35,917 $\pm$ 191.0 ^{ef}	33.74 $\pm$ 0.76 ⁱ	40 $\pm$ 0.2 ^t	70 $\pm$ 0.5 ^m
Guar gum	1	GG4	152.2 $\pm$ 0.36 ^a	437.3 $\pm$ 0.98 ^v	2.87 $\pm$ 0.01 ^{ij}	1096 $\pm$ 4.0 ^{ef}	32,804 $\pm$ 105.5 ^{gh}	29.92 $\pm$ 0.32 ^p	36 $\pm$ 0.1 ^r	72 $\pm$ 0.5 ^l
Xanthan gum	0.25	XG1	155.5 $\pm$ 1.21 ^l	447.5 $\pm$ 0.55 st	2.88 $\pm$ 0.023 ^{gh}	1297 $\pm$ 32.1 ^{gh}	33,844 $\pm$ 628.9 ^{ge}	26.12 $\pm$ 1.13 ^r	38 $\pm$ 0.7 st	72 $\pm$ 0.8 ^l
Xanthan gum	0.5	XG2	152.9 $\pm$ 0.5 ^m	449.1 $\pm$ 1.25 ^{uv}	2.94 $\pm$ 0.003 ^o	1389 $\pm$ 32.1 ⁿ	29,700 $\pm$ 62.8 ^a	21.38 $\pm$ 0.40 ^s	33 $\pm$ 0.7 ^u	70 $\pm$ 0.2 ^m
Xanthan gum	0.75	XG3	155.5 $\pm$ 1.14 ⁿ	398.9 $\pm$ 2.29 ^{tu}	2.57 $\pm$ 0.033 ^p	1316 $\pm$ 27.1 ^o	33,093 $\pm$ 782.0 ^{ac}	25.16 $\pm$ 1.13 ^t	37 $\pm$ 0.9 ^{rs}	73 $\pm$ 0.4 ^k
Xanthan gum	1	XG4	151.1 $\pm$ 0.33 ^a	387.6 $\pm$ 1.26 ^{rt}	2.57 $\pm$ 0.013 ^{op}	1314 $\pm$ 3.6 ^p	32,876 $\pm$ 347.2 ^{bd}	25.02 $\pm$ 0.30 st	37 $\pm$ 0.4 ^{tu}	71 $\pm$ 0.6 ^k

Data represents means of three samples ($n=3$) $\pm$ s.dMeans with the same superscript within the same column are not significantly different ($p>0.05$)

A two-bite crumb compression test was performed by compressing axially each sample with a 40 mm diameter flat plate probe attached to the moving crosshead. The testing conditions were: compression ratio of 50 % deformation from the initial height of the sample; 20 mm/min crosshead speed and 20 mm/min chart speed. The force-distance curve obtained was used to derive the firmness of the crumb (Bourne 1978).

The bread loaves after cooling were stored in the refrigerator (approx. $4\pm 2^\circ\text{C}$) in metallised food bags (Zipfoil®) for 1, 3, 5, 7 and 14 days and crumb moisture and firmness measured at respective days.

Avrami's firming kinetics

The bread firmness values measured at 0, 1, 3, 5, 7 and 14 days of storage were fitted into the Avrami's non-linear regression equation (Armero and Collar 1998; Angioloni and Collar 2009):

$$\theta = \frac{T_\infty - T_t}{T_\infty - T_0} = e^{-k \cdot t^n} \quad (2)$$

where,

- θ fraction of starch recrystallisation still to occur,
- T_0 crumb firmness of fresh bread,
- T_∞ final crumb firmness,
- T_t crumb firmness in 't' time,
- k rate constant and
- n Avrami exponent

The rate of firming of bread could be quantitatively analyzed by the Avrami equation, which was developed to describe the equilibrium crystallization of high polymer melts. The Avrami exponent n is related to the way of crystal nucleation and its subsequent growth (Armero and Collar 1998; Haros et al. 2002). 'k' in the Eq. 2 is useful in calculating the time constant (1/k) which helps in interpreting the rate of firming.

Crumb grain analysis

Crumb grain characteristics of the bread loaves were assessed using a digital image analysis system. The bread loaves were sliced transversely. They were then scanned in colour using a flatbed scanner with a resolution of 300 dpi. The scanned images were then analyzed using Image J software (<http://rsb.info.nih.gov/ij>) (Turabi et al. 2010; Ozkoc et al. 2009). The centre of each slice was cropped in a square of $300 \times 300 \text{ mm}^2$ and converted to grey scale (8-bit). For simplicity a 1:1 ratio was maintained while converting pixel into mm. After adjusting the threshold, total no. of cells, total cell area,

average cell area, small cell to large cell ratio were determined using the software.

Dough rheology

The dough samples prepared for the dynamic rheological tests consist of the same formulation as that of the bread samples, without yeast. Dynamic oscillatory tests were performed in a controlled stress rheometer, (Physica MCR 51 Anton Paar, Germany). Parallel plates of 49.986 mm and 2 mm gap were used and the measurements monitored with RheoPlus software package (version 2.65). A temperature of 25°C was kept during the analyses with a water circulator device (Neslab RTE 7, Refrigerated Bath, Thermo Electron Corporation, USA). All samples were allowed to rest for 5 min before measurements to allow dough relaxation. Frequency-sweep tests of the dough samples were performed at a constant strain of 1 % and angular frequency ranging between 0.1 and 200 ω . Dynamic moduli G' , G'' and $\tan \delta$ (G''/G') were obtained as a function of frequency. G' is the dynamic elastic or storage modulus, related to the material response as a solid, while G'' is the viscous dynamic or loss modulus, related to the material response as a fluid. $\tan \delta$ is related with the overall visco-elastic response: low values of this parameter indicate a more elastic nature.

Statistical analysis

All the studies were replicated three times and the means reported. All the experimental data were analyzed statistically for analysis of variance (ANOVA) with Microsoft Excel 2007. Means were compared by Fisher's Least Significant Difference Test at a significance level of $p \leq 0.05$.

Results and discussion

Bread quality

Loaf size

Addition of 3.0 % coriander leaf powder was seen to increase the loaf weight significantly while decreasing the loaf volume. Further addition of hydrocolloids to the 3.0 % coriander bread marginally increased the loaf weight. However, the loaf volume of the bread samples with hydrocolloids was significantly higher than CON. The loaf volume broadly had a decreasing trend with the increasing percent of hydrocolloids with exceptions for GG3 and XG2. Such a behavior may infer that smaller amounts of hydrocolloids are more effective on loaf volume (Kohajdová et al. 2009) though it may also depend on the nature of the hydrocolloid and its chemical structure.

Fig. 1 Crumb grain characteristics of breads (a) control white, (b) 3 % coriander bread, (c) 3 % coriander bread with different levels of CA, (d) 3 % coriander bread with different levels of CMC, (e) 3 % coriander bread with different levels of GG and (f) 3 % coriander bread with different

levels of XG. [i] Cross-sectional image of actual bread crumb, [ii] binary image showing the cell structure after image processing. Refer Table 1 for sample codes

The specific volume of COR was found to be lowest (2.33 ml/g) because of a significantly higher loaf weight yet almost unchanged loaf volume with respect to CON. Higher values of specific volumes were seen consistently amongst almost all the bread samples with hydrocolloids

(Table 1). This may be attributed to the fact that hydrocolloid addition causes higher water retention in the samples, contributing to better gluten development (Rodge et al. 2012). In this regard Mikuš et al. (2011) stated that hydrocolloids were able to modify gluten and starch properties by mainly influencing

Fig. 1 (continued)

gluten hydration. This facilitates more gas to be entrapped in the dough thereby increasing the overall loaf volume.

Crumb grain characteristics

The crumb grain characteristics of the samples were studied using image analysis on the basis of certain image properties namely the total number of cells in a defined crumb area, the total cell area, average cell size, the total cell area to total area ratio and the small cell ($\leq 2 \text{ mm}^2$) to large cell ($\leq 10 \text{ mm}^2$)

ratio. Figure 1a, b, c, d, e, f shows the bread crumbs and their respective images obtained from the Image J software.

While comparing the total number of cells in a defined area (Table 1), a marked increase was seen in samples with hydrocolloids. COR was found to have the largest average cell area (48.08 mm^2). It was observed that average cell size in hydrocolloid supplemented samples were consistently lower than CON (34.21 mm^2). The total cell to total area ratio parameter was used to express the void fraction in the measured area, i.e. relative porosity (Švec and Hrušková 2004). This ratio was found to be highest for the COR (45 %) whereas on

Fig. 2 Changes in crumb firmness (a) and crumb moisture content (b) of the bread samples with or without hydrocolloids during storage at refrigerator. Refer Table 1 for sample codes. Data represents means of three samples ($n=3$) $\pm$ s.d

hydrocolloid addition the values ranged between 32 and 43. A combination of factors such as a high total cell area to total area ratio and low number of cells explains higher average cell area size in breads with hydrocolloid. The relative distributions of cell sizes were studied by measuring the ratio of small cells (area $\leq 2 \text{ mm}^2$) to larger cells with areas $\leq 10 \text{ mm}^2$. Results showed that irrespective of the addition of either coriander or hydrocolloids the ratio was more or less around 70 % except for GG2. This explains the effects of hydrocolloid in improving the crumb grain characteristics (Kohajdová et al. 2009; Rodge et al. 2012) by increasing the relative number of small cells. A probable explanation behind this observation may be the stabilization of the air cells in the dough on application of hydrocolloids which prevents coalescence of the cells. Several very

large cells were also noticed on slice's area, a well known characteristic of flours with disturbed viscoelastic properties (Scanlon et al. 2000; Zghal et al. 2001).

Relationship between specific volume and average cell area

A study performed on the specific volumes of the samples and the corresponding average cell area for showed inverse relation to the average cell area for almost all the cases. This relationship may be reasoned by the fact that i) addition of hydrocolloids inhibits the formation of bigger cells and ii) a larger number of small cells creates a uniform crumb matrix preventing the CO_2 gas present in the sample to escape thereby increasing the loaf volume.

Crumb moisture and crumb firmness

Changes in crumb firmness and crumb moisture are the most conspicuous quality changes in baked products during storage to indicate the staling process (Shittu et al. 2009). Figure 2a and b shows the crumb firmness and crumb moisture content of the bread samples with and without hydrocolloid with storage days respectively. Application of XG caused a uniform change in crumb moisture over storage at all levels of supplementation. Maximum loss of moisture during storage was consistently observed for all levels of GG possibly due to higher rate of retrogradation. It was observed that in most of the bread samples with hydrocolloids (with the exception of CA4 & XG3), the change in the firmness values from 0 day to 7 days was less than that in CON. This may point to a slower rate of firming on application of hydrocolloids. A possible reason behind this observation may be the higher moisture retention by hydrocolloids in the final baked products resulting in reduced starch retrogradation (Sharadanand and Khan 2003; Kohajdová and Karovičová 2009).

The Figures also suggested a typical inverse relationship between crumb moisture and crumb firmness with increasing number of days in storage. (Rogers et al. 1988; He and Hosney 1990). Bread firmness may be caused by the formation of cross-links between partially solubilised starch and gluten proteins (Martin et al. 1991). In bread, water acts as a plasticizer. When moisture decreases, it may accelerate the formation of cross links between starch and protein and, thus, the bread may firm faster (He and Hosney 1990). The decreasing and increasing effects on crumb moisture and firmness respectively may vary with different hydrocolloids due to their different molecular structures and their interaction with the starch molecules.

Fig. 3 Relationship between ‘n’ and ‘k’ of Avrami equation using scattered plots for breads prepared with different levels of hydrocolloids and 3 % coriander leaf powder. Refer Table 1 for sample codes

Crumb firming kinetics

The process of bread making is known to be a complex process. Crumb firming is mainly caused by changes in starch structure. The starch in wheat flour is made up of straight and branched chains. During baking the starch granules swell and the straight chains diffuse out, then as the bread cools the straight chains link together to provide the loaf’s initial shape and strength. The branched chains of starch remain in the granules during baking and link together slowly during storage to make the crumb progressively more firm with time (Angioloni and Collar 2009). Previous studies reported n to be unity suggesting starch crystallization to be an instantaneous nucleation process followed by linear growth of crystals (Kim and D’Appolonia 1977; MacIver 1969). However, recent publications (Armero and Collar 1998; Martin et al. 1991) showed that Avrami exponent was different to one suggesting the fact that bread staling is the result of several effects and starch retrogradation is not the only cause (Zobel and Kulp 1996). It is known that gluten changes during bread storage and water migration from gluten to starch contributes significantly in bread staling (Wilhoff 1971). The Avrami equation is still considered to be an important mathematical tool

Table 2 Rheological properties of bread dough containing different levels of hydrocolloids and 3 % coriander leaf powder

Sample codes*	Frequency sweep test parameters		
	G^* (Pa)	$\tan(\delta)$	$ \eta ^*$ (Pa.s)
CON	8230±850 ^a	0.48±0.01 ^m	1340±140 ^e
COR	12967±1168 ^b	0.51±0.02 ^m	2103±188 ^f
CA1	13967±503 ^c	0.51±0.01 ^m	2273±81 ^g
CA2	14067±1047 ^d	0.47±0.08 ^m	2320±139 ^h
CA3	15533±1701 ^e	0.52±0.01 ⁿ	2523±280 ^{ef}
CA4	14124±548 ^f	0.47±0.01 ^m	2300±141 ^{gh}
CMC1	14700±985 ^g	0.53±0.02 ^p	2387±157 ⁱ
CMC2	17893±1299 ^h	0.50±0.03 ^m	2910±190 ^{ij}
CMC3	15367±850 ⁱ	0.55±0.01 ^q	2497±138 ^j
CMC4	16442±591 ^j	0.53±0.01 ^r	2662±145 ^{kl}
GG1	18767±1115 ^k	0.50±0.01 ^m	3053±187 ^k
GG2	14478±696 ^l	0.49±0.02 ^m	2350±165 ^l
GG3	16867±874 ^m	0.53±0.02 ^s	2733±139 ^m
GG4	14066±669 ⁿ	0.52±0.01 ^t	2290±180 ^{mn}
XG1	16800±1300 ^o	0.49±0.02 ^m	2733±210 ⁿ
XG2	14703±504 ^p	0.45±0.01 ^m	2390±130 ^{op}
XG3	22500±1000 ^q	0.48±0.02 ^m	3653±165 ^{pq}
XG4	20574±820 ^r	0.43±0.0 ^o	3340±171 ^{oq}

*Refer Table 1 for sample codes

Data represents means of three samples ($n=3$)±s.d

Means with the same superscript within the same column are not significantly different ($p>0.05$)

offering kinetics which fit observed data. Previous literatures on crumb firming kinetics (Armero and Collar 1998; Haros et al. 2002) suggest that the Avrami parameters, n and k have a strong correlation between themselves. Figure 3 depicts the relation between n and k in a scatter plot.

The values of n in this study were also found out to be different from unity. Figure 3 shows that both CON and COR have similar k value suggesting similar rates of development of hardening during storage. Application of CA and CMC in certain samples was found to decrease the value of k suggesting an inhibiting effect on the firming rate. For GG and XG, the k value was almost consistently higher than the both the CON or COR pointing an enhanced rate of retrogradation.

A higher n or k value is known to fasten the crumb firming kinetics. Such results were seen in certain cases like XG (higher k values) and CA (higher n values). No observations were seen where both n and k were high. Such observations would have meant a very fast crumb firming kinetics. However, majority of the observations were seen in the lower half plane to the left suggesting low values for both n and k . This suggests an especially slow firming kinetics. Overall GG and CMC seem to be more consistent in slowing down the down crumb firming kinetics.

Dough rheology

From the basic rheological data, the shear stress was found to be a monotonically increasing function of shear rate with decreasing gradient suggesting the pseudo-plastic nature of all the bread samples. Sweep tests were performed to further investigate the effects of hydrocolloids on the rheological parameters such as G' , G'' and $\tan(\delta)$. Amplitude sweep tests of the bread samples suggested a profile where both G' and G'' decreases with increasing stress. The crossover points ($G' = G''$) in the profile gives an idea of the flow stress in the samples. The crossover point was found to be higher in the hydrocolloid supplemented bread samples. Analysis into the linear visco-elastic (LVE) region suggested the use of 1 % strain in frequency sweep tests for all bread samples.

From the frequency sweep tests, the $\tan(\delta)$ value was found to be in the range of 0.43–0.55 suggesting that G' values were around twice as large as G'' (Table 2). As such the complex modulus (G^*) values were dominated by the storage component over the loss component. The G^* value in COR was considerably higher than CON. The results however varied in case of the dough with hydrocolloids indicating that both the type and level of supplementation played a role. The highest G^* values were seen for XG3 and XG4. The frequency sweep profile also showed complex viscosity as a monotonically decreasing function with decreasing gradient of angular frequency.

Conclusion

The addition of hydrocolloids was found to improve the crumb quality significantly due to increased loaf volume, specific volume and a uniform texture owing to an increased porosity. In the current study, a n inverse relation was been established between specific volume and average cell area. The role of hydrocolloids in moisture retention was consistent in case of XG, followed by CA and CMC. Avrami's crumb firming kinetics showed that GG and CMC had better effect in lowering firming rate. Hydrocolloids increased the complex modulus, most notably in XG.

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