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Effects of purified monoglycerides on Canadian short process and sponge and dough mixing properties, bread quality and crumb firmness during storage ☆

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ABSTRACT

The effects of increasing levels of a wide range of purified saturated (C12:0–C22:0) and unsaturated (C18:1 *cis*, C18:1 *trans*, C18:2, C18:3) monoglycerides on Canadian short process (CSP) and sponge and dough (SDP) mixing properties, bread quality and crumb firmness during storage have been studied. For both processes, higher levels (0.5–1.0%) of polyunsaturated monoglycerides (C18:2, C18:3) caused the largest significant ($p < 0.05$) increases in mixing time and mixing energy requirements while shorter chain saturated monoglycerides (C12:0, C14:0) significantly increased mixing time and energy requirements for the CSP. Most monoglycerides had positive effects on CSP loaf volume and bread score while no improvement was evident for the SDP. For both processes, crumb firmness during storage was significantly reduced by addition of C16:0 and C18:0 saturated and *cis*- and *trans*- monounsaturated monoglycerides and was significantly increased by addition of C12:0 and the polyunsaturated monoglycerides. Changes in crumb firmness during storage were attributed to the effects of monoglycerides on both initial crumb firmness and the rate of crumb firming. The baking process appeared to have a strong influence on the relative impact of monoglycerides on overall crumb firmness and, in particular, initial firmness.

1. Introduction

Monoglycerides are widely used as anti-staling agents and account for approximately one third of the emulsifiers used in the baking industry (Stauffer, 2000). These compounds can also act as mild dough conditioners, leading to improved dough machining properties, enhanced slicing performance and superior bread quality (Knightly, 1968; Knightly, 1988; Maga, 1975; Stampfli & Nersten, 1995). The anti-staling properties of monoglycerides are generally attributed to their ability to complex with the major starch components, amylose and amylopectin (Knightly, 1988; Stampfli & Nersten, 1995). Most studies have shown that monoglycerides reduce the rate of staling (crumb firming) rather than influence the initial crumb firmness (Knightly, 1988).

Commercial monoglycerides, on which much of the above information is based, are normally prepared from hydrogenated fats with stearate (C18:0) being the most common fatty acid (Batres & White, 1986). The performance of purified monoglycerides prepared from other fatty acids is less well documented. Their effects on the physical dough properties of full formula dough have not been assessed. With simpler flour–water dough systems, addition of glycerol monostearate caused a slight reduction in farinograph mixing requirements (Horubalowa, Jakubczyk, & Pasturczak, 1975; Tsen & Weber, 1981) and stability (Amero & Collar, 1996). Glycerol monostearate and monooleate (C18:1*cis*) have also been shown to reduce Extensigraph height and increase extensibility (Horubalowa et al., 1975; Knightly, 1968). This "dough softening" effect may account for the improved dough handling properties of bread dough containing monoglycerides (Bajwa, 1990; Knightly, 1988).

The majority of earlier studies generally concluded that monoglycerides do not have a major influence on loaf volume (Kulp & Ponte, 1981). However, Riisom, Krog, and Eriksen (1984) demonstrated that saturated monoglycerides increased the volume of bread to a greater extent than unsaturated monoglycerides in bread prepared following a straight dough process and containing no other fat. *Trans*- unsaturated fatty acid monoglycerides were more effective than those of *cis*- conformation. Using a full formula sponge and dough (SDP) process, Inoue, Tsugita, Koike, Maruzeni, and Kamoi (1995) found that unsaturated monoglycerides (monooleate and monoelaidate) increased bread volume relative to monostearate, a saturated monoglyceride.

Several studies have shown that the anti-staling properties of monoglycerides containing longer chain saturated fatty acids are superior to those containing unsaturated fatty acids (Coppock,

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Cookson, Laney, & Axford, 1954; Baldwin, Titcomb, Johansen, Keogh, & Koedding, 1965; Doerfert, 1968; Lagendijk & Pennings, 1970). Other studies have shown that unsaturated monoelaidate (C18:1*trans*) was equally effective compared with saturated monopalmitate (C16:0) as an anti-staling agent, while the *cis*- unsaturated monooleate was less effective (Inoue et al., 1995; Riisom et al., 1984). Joensson, as reported by Knightly (1988), demonstrated that the position of the fatty acid (*sn*-1 or *sn*-2) does not have an influence on monoglyceride performance.

The most comprehensive study of saturated monoglyceride anti-staling performance was carried out by Lagendijk and Pennings (1970), using a straight dough procedure containing shortening. Their results showed that longer chain C14:0 to C18:0 fatty acids (monomyristate, monopalmitate and monostearate) gave superior performance relative to shorter monolaurate (C12:0) and the very long monobehenate (C22:0). Monopalmitate gave the softest crumb after both 48 and 72 h storage, consistent with studies by Riisom et al. (1984). The results of Lagendijk and Pennings's study have been widely quoted as evidence for the relationship between staling and monoglyceride starch binding (Knightly, 1988).

In the present paper, we report a comprehensive study of the effects of a wide range of purified saturated (C12:0–C22:0) and unsaturated (C18:1 *cis*, C18:1 *trans*, C18:2, C18:3) monoglycerides at different concentrations on the mixing properties, bread quality and crumb firmness during bread storage, using a Canada Western Red Spring (CWRS) straight grade wheat flour. Since several workers (Baldwin et al., 1965; Bell, Daniels, & Fisher, 1977) have pointed out that formulation and processing conditions appear to have an important impact upon monoglyceride performance, results are presented for both no-time Canadian short process (CSP) and SDP laboratory scale baking processes designed to mimic commercial processes used in Canada and Japan, respectively.

2. Materials and methods

2.1. Flour testing

Straight grade flour was prepared from No. 1 CWRS wheat on the Canadian International Grains Institute pilot mill (Buhler AG, Uzwil, Switzerland). Flour protein content (12.7% on 14% moisture basis) was measured by combustion nitrogen analysis using a LECO model FP-248 Dumas CNA analyzer (LECO Corp. St. Joseph, MI). Flour ash content (0.55% on 14% mb) and farinograph parameters were measured following AACC official methods 08-01 and 54-21, respectively (AACC 2000). Farinograph dough development time was 6.5 min at an optimum absorption of 64.0%.

2.2. Monoglyceride preparation

Monoglycerides were prepared as described by Inoue et al. (1995). Pure (>99%) fatty acids were obtained from Asahi Denka Kogyo, Tokyo (lauric acid C12:0, myristic acid C14:0, palmitic acid C16:0), Nihon Yushi, Tokyo (stearic acid C18:0, behenic acid C22:0), Tokyo Kasei Kogyo, Tokyo (oleic acid C18:1 *cis*, linoleic acid C18:2) and Wako Junyaku, Tokyo (elaidic acid C18:1 *trans*, linolenic acid C18:3). Pure glycerin was obtained from Asahi Denka Kogyo, Tokyo. Briefly, fatty acid was reacted with glycerin at a 1:4 molar ratio in the presence of KCO_3 (0.5% w/w glycerin) as catalyst at 200 °C at a pressure of 200 mm Hg for 2 h in a closed vessel. After cooling to room temperature, excess glycerin was decanted from the crystallised product containing mono-, di- and tri-glycerides. Monoglycerides were recovered from the mixture by molecular distillation at 200 °C at 0.004 mm Hg pressure and further purified by Florisil column chromatography. All monoglycerides were >99% pure as assessed by thin layer chromatography on coated rods with flame ionisation detection and were in the form of white paste-like semi-solids. The physical state of the purified monoglycerides allowed for easy weighing of each monoglyceride for addition directly to the respective bread dough formulation.

2.3. Baking procedures

The CSP baking procedure was performed as previously described (Yamada & Preston, 1992). Dough ingredients included flour (100 g, 14.0% moisture basis), fresh compressed yeast (3.0 g), salt (2.4 g), sucrose (4.0 g), ammonium phosphate (0.1 g), ascorbic acid (150 ppm), 60 °L malt syrup (0.2 g), shortening (3.0 g), monoglyceride (variable, see below), whey (4.0 g) and optimum water (68% absorption for all monoglyceride treatments) as assessed by dough feel by an experienced baker at panning. Ingredients were mixed in a GRL 200 mixer at 165 rpm to 10% past peak consistency at 30 °C. The dough was rested 15 min (30 °C), punched lightly seven times, and rounded by hand and given an intermediate proof of 15 min (30 °C). Dough was then sheeted three times (8.7, 4.8 then 3.2 mm), moulded on the GRL moulder, panned and proofed for 70 min at 37.5 °C (87% rh). The bread dough was then baked in heat sink ovens for 25 min at 195 °C, as previously described (Kilborn, Preston, & Kubota, 1990).

A SDP procedure similar to that used in Japan was performed as previously described (Yamada & Preston, 1994). Sponge ingredients included flour (70 g), fresh compressed yeast (2.2 g), salt (0.15 g), ammonium phosphate (0.1 g), 60 °L malt syrup (0.2 g), ascorbic acid (40 ppm) and water (70% of the final bake absorption). Ingredients were mixed for 2.5 min at 135 rpm in a GRL 200 mixer at 27 °C and fermented for 270 min at 27 °C (90% rh). The sponge and remaining ingredients including flour (30 g), salt (2.25 g), sucrose (5.0 g), shortening (3.0 g), monoglyceride (variable, see below), skim milk powder (2.0 g), malt syrup (0.1 g) and optimum water (66% for all monoglyceride treatments), as assessed by dough feel by an experienced baker at panning were then mixed to 10% past peak (GRL 200 mixer, 135 rpm) at 30 °C. Dough was rested, punched, given an intermediate proof, sheeted, moulded, panned, proofed and baked as described above for the CSP.

2.4. Measurement of dough and bread properties

Mixing time and mixing energy to peak were obtained using a GRL watt–hour meter attached to the GRL 200 mixer (Kilborn, 1979). Dough sheeting energy (sum of 2nd and 3rd sheetings) was obtained by means of a force transducer attached to the arm of the sheeter as previously described (Kilborn & Preston, 1982). The signal from the transducer was digitised and amplified, and the resulting force - time (length) curve integrated to obtain sheeting energy using LABTECH Notebook version 7.2.1 (LABTECH, Wilmington, MA). Bread volume, crust appearance, crumb colour, crumb texture and total bread score were assessed by an experienced baker, as described previously (Preston, Kilborn, & Black, 1982b). Crumb firmness was determined by measuring compression force at 50% deformation for three stacked bread slices (38 mm total height) using the GRL compression tester, as described by Kilborn, Tipples, and Preston (1983). All loaves were stored at room temperature in plastic bags and sliced just prior to compression.

2.5. Experimental design for testing monoglycerides

For each experiment, surfactant was added at four different levels (0, 0.25, 0.50 and 1.00%). A randomised block design was applied and the results analysed by analysis of variance (ANOVA) (SAS Institute, Cary, NC). Appropriate means were compared for significance at the 5% level using Duncan's multiple range tests.

Three blocks baked on different days with three loaves per block were used to obtain mixing energy, mixing time, total sheeting work and loaf volume. The three loaves from each block were then used to measure crumb firmness at 24, 48 and 72 h after baking. For crumb and crust characteristics and bread score, three additional blocks (one loaf per block) were baked and scored for these parameters.

3. Results and discussion

3.1. Effects of monoglycerides on dough mixing properties

Preliminary studies showed that optimum water absorption, as assessed by dough feel at panning, did not vary with monoglyceride type or level. This result is consistent with previous studies showing that farinograph absorption is not strongly influenced by a wide range of surfactants (Knightly, 1968; Tsen & Weber, 1981; Bajwa, 1990). The effects of surfactant type and level on CSP dough mixing properties are shown in Table 1. ANOVA showed significant increases in mixing energy to peak with increasing monoglyceride level (0.0, 0.25, 0.50 and 1.00%), for all fatty acid chains except C18:0 and C22:0. Similar results were obtained for mixing time. Increasing concentrations of all monoglycerides except C22:0 caused significant increases in mixing time to peak. In general, the longer chain saturated monoglycerides (C16:0, C18:0 and C22:0) had the least impact on mixing properties, while the polyunsaturated (C18:2 and C18:3) monoglycerides had the greatest effect. Although the largest effects were evident at the 1.0% level, addition of 0.5% monoglyceride, which represents the upper level normally used commercially, also significantly ($p < 0.05$) increased mixing energy and time in all but one case when the overall level effect was significant.

Mixing energy and mixing time requirements for the SDP were shorter than those required for the CSP (Table 1). The SDP mixing response to increasing levels of polyunsaturated and longer chain saturated monoglycerides was similar to that obtained with the CSP. Addition of the former resulted in significant increases in both mixing parameters while no significant increases were apparent with the latter. In contrast to CSP results, addition of shorter chain saturated monoglycerides (C12:0 and C14:0) had little or no effect upon mixing energy and time. The C18:1 *cis* monoglyceride increased mixing energy and mixing time to a greater extent than the C18:1 *trans* monoglyceride, whereas, with the CSP, the *cis* form had a larger impact on mixing time while the *trans* form of the monoglyceride had a greater effect on mixing energy requirement.

No studies on the impact of different monoglycerides on the mixing properties of full formula dough were found in the published literature. The present study demonstrates that monoglyceride type and level, as well as baking process, can have a strong influence on these properties. The minimal effect of longer chain saturated monoglycerides on CSP and SDP mixing properties is consistent with results obtained with flour–water dough in the farinograph (Horubalowa et al., 1975; Knightly, 1968; Tsen & Weber, 1981; Bajwa, 1990; Inoue et al., 1995). The large significant effects of the unsaturated monoglycerides on mixing properties suggest a dough strengthening effect, consistent with Extensigraph results obtained when *cis*- and *trans*-unsaturated C18:1 monoglycerides were added to flour–water–salt dough (Inoue et al., 1995). Differences due to baking process were most evident with the shorter chain monoglycerides, which significantly increased mixing requirements for the CSP but had little impact on the SDP.

Although several theories have been postulated to account for the general strengthening effect of surfactants (Stampfli & Nersten, 1995), results from the present study are most consistent with the theory that surfactants exert their effect by binding to the gluten

Table 1
Effects of monoglyceride level on CSP and SDP dough mixing properties[a].

Level	12:0	14:0	16:0	18:0	22:0	$18:1_{cis}$	$18:1_{trans}$	18:2	18:3
CSP mixing energy to peak (Wh/kg)[d]									
0.00%	7.3	6.9	7.2	7.4	7.2	7.2	7.4	7.4	7.3
0.25%	8.1	7.3	7.8	7.5	7.2	7.6	7.6	7.8	7.8
0.50%	8.2	7.3	8.0	7.7	7.5	8.0	8.8	7.9	8.5
1.00%	8.5	8.6	8.4	8.0	7.6	8.3	8.7	9.1	9.0
CR(DUN)[b]	0.89	0.83	0.69	0.68	0.55	0.87	0.89	0.86	1.01
SIG(ANOVA)[c]	*	***	**	NS	NS	*	**	**	**
CSP mixing time to peak (min)[d]									
0.00%	9.3	9.4	9.3	9.6	9.3	9.5	9.2	9.6	9.5
0.25%	10.2	9.8	9.7	9.8	9.4	10.3	9.6	10.3	10.5
0.50%	10.6	10.1	9.8	10.0	9.6	11.3	10.8	11.1	11.6
1.00%	11.1	10.9	10.1	10.1	9.8	12.6	11.1	13.3	13.0
CR(DUN)[b]	0.66	0.45	0.48	0.39	0.64	0.67	0.77	0.71	0.61
SIG(ANOVA)[c]	***	***	**	*	NS	***	***	***	***
SDP mixing energy to peak (Wh/kg)[d]									
0.00%	4.8	4.6	4.8	4.7	4.9	4.8	4.7	4.5	4.8
0.25%	4.7	4.8	4.9	4.9	4.8	4.7	4.7	4.9	4.8
0.50%	4.6	4.7	5.0	4.6	4.8	5.2	4.9	5.2	4.9
1.00%	4.8	5.2	4.6	4.9	4.8	5.8	5.1	6.0	5.3
CR(DUN)[b]	0.36	0.36	0.37	0.33	0.41	0.35	0.44	0.42	0.28
SIG(ANOVA)[c]	NS	**	NS	NS	NS	***	NS	***	***
SDP mixing time to peak (min)[d]									
0.00%	5.7	6.1	5.9	5.6	6.0	5.7	5.6	5.5	5.9
0.25%	5.5	6.2	6.1	5.7	6.0	5.7	5.9	6.0	5.9
0.50%	5.5	6.0	6.0	5.7	5.9	6.3	5.8	6.5	6.3
1.00%	5.8	6.5	5.9	5.7	6.0	7.3	6.1	8.0	7.6
CR(DUN)[b]	0.39	0.54	0.40	0.08	0.15	0.25	0.39	0.18	0.44
SIG(ANOVA)[c]	NS	NS	NS	NS	NS	***	*	***	***

[a] Values represent mean of 3 blocks (1 firmness result per block).
[b] Critical range for significant difference ($p < 0.05$) between monoglyceride levels for Duncans multiple range tests.
[c] Anova *F* value probability of significant level effect, * = 5%, ** = 1%, *** = 0.1%, NS = not significant.
[d] Standard deviations: CSP mixing energy to peak = ±0.16; CSP mixing time to peak = ±0.15; SDP mixing energy to peak = ±0.12; SDP mixing time to peak = ±0.20.

proteins, resulting in enhanced gluten protein interactions *via* reduced electrostatic repulsion and/or increased hydrophilic/hydrophobic interactions (Chung, Tsen, & Robinson, 1981; Green & Kasarda, 1971). Previous studies have demonstrated that longer chain unsaturated monoglycerides (C18:1 *cis*, C18:1 *trans* and C18:2) show a much stronger tendency to bind to gluten proteins, relative to saturated (C16:0 or C18:0) monoglycerides for continuous (Baldwin et al., 1965), straight dough (Riisom et al., 1984) and sponge- and -dough (Inoue et al., 1995) bread processing. The possibility that this differential surfactant binding could influence dough strength by altering starch – protein binding must also be considered. There is evidence that differences in starch – protein binding could play a major role in determining dough strength properties (Edwards, Dexter, & Scanlon, 2002; Petrofsky & Hoseney, 1995).

3.2. Effects of monoglycerides on bread quality

The effects of increasing levels of monoglycerides on CSP and SDP loaf volume are shown in Table 2. With the exception of the longest chain fatty acid (C22:0), ANOVA showed that saturated monoglycerides had significant positive effects upon CSP loaf volume. The C18:1 *cis* and C18:3 unsaturated monoglycerides also had significant positive effects upon loaf volume, while the remaining unsaturated monoglycerides (C18:1 *trans* and C18:2) had no significant effect upon this parameter. In contrast to these results, addition of monoglycerides, with the exception of C14:0, did not result in significant increases in SDP loaf volume. In general, the effects of adding monoglycerides on CSP and SDP total bread scores showed the same trend as that obtained for loaf volume (data not shown).

Most studies have shown that commercial monoglycerides, containing primarily monostearate (C18:0), have minimal effects on loaf volume, as reviewed by Kulp and Ponte (1981). However, significant increases in loaf volume have been demonstrated in no-fat straight dough bread (Riisom et al., 1984) with selected purified saturated and unsaturated monoglycerides, including monopalmitate (C16:0), monoelaidate (C18:1 *trans*), monooleate (C18:1 *cis*) and monolinoleate (C18:2). Kohler and Grosch (1999) found that loaf volumes of no-fat straight dough containing synthesised DATEM, derived from saturated monoglycerides ranging from C6:0 to C22:0 increased significantly with increasing fatty acid chain length up to C18:0. Riisom et al. (1984) found that the monopalmitate and monoelaidate were more effective than the other two monoglycerides. For SDP bread Inoue et al. (1995) found increases in loaf volumes with glycerol monoelaidate and monooleate but not with monostearate. The present study, involving a much wider range of monoglycerides, suggests that the choice of baking process plays an important role in determining the impact of monoglycerides on bread quality. The generally positive loaf volume response obtained for almost all monoglycerides with the CSP process may be a reflection of their ability to act as shortening replacers, leading to enhanced handling properties (Stampfli & Nersten, 1995) and increased gas cell stability during baking (Bell et al., 1977). For the SDP, the well known mellowing effect of sponge fermentation (Preston & Kilborn, 1982a) probably reduces the need to add monoglycerides in order to optimise dough handling properties and gas cell stability. This supposition was supported by data obtained by measuring the sheeting properties of dough during processing. Although sheeting measurements showed wide variations which resulted in poor reproducibility, addition of increasing levels of 7 of the 9 monoglycerides resulted in a reduction in sheeting energy (3 significant at $p < 0.05$), while no trend was evident with the SDP (data not shown).

3.3. Effects of monoglycerides on crumb firmness during storage

ANOVA of the crumb firmness data for the four levels of each monoglyceride (0, 0.25, 0.50 and 1.00%), measured after 24, 48 and 72 h, showed that, with the exception of C18:1 *trans*, no significant interactions occurred between storage time and monoglyceride level with either baking process. Data were therefore combined by level (Table 3) or by storage time (Table 4) for further analysis.

The effects of monoglyceride level averaged over the three storage times on compression force are shown in Table 3 for the CSP and SDP. For the CSP, ANOVA showed that the shortest chain saturated monoglyceride (C12:0), as well as both polyunsaturated monoglycerides (C18:2 and C18:3), significantly ($p < 0.001$ or <0.01) increased crumb firmness with increasing level. The level of C14:0 and C22:0 monoglycerides had no significant impact on this parameter. It was of interest that the addition of C14:0 resulted in the greatest relative increase in volume of all of the monoglycerides under both baking regimes, which would be expected to result in softer crumb. As there was no significant difference in crumb softness for either bread type upon addition of C14:0, it would be reasonable to surmise that this monoglyceride was causing a small increase in crumb firmness that was offset by the increased softness resulting from increased loaf volume. The remaining saturated monoglycerides (C16:0 and C18:0) and both monounsaturated monoglycerides significantly ($p < 0.001$) re-

Table 2
Effects of monglyceride level on CSP and SDP loaf volume[a].

Level	12:0	14:0	16:0	18:0	22:0	$18:1_{cis}$	$18:1_{trans}$	18:2	18:3
CSP loafvVolume (cm^3)[d]									
0.00%	1047	1053	1097	1032	1082	1083	1079	1088	1075
0.25%	1091	1064	1122	1071	1068	1093	1066	1089	1121
0.50%	1104	1118	1114	1092	1091	1120	1082	1081	1101
1.00%	1102	1133	1137	1086	1079	1122	1087	1064	1118
CR(DUN)[b]	45	27	37	34	51	32	36	37	33
SIG(ANOVA)[c]	*	***	*	**	NS	*	NS	NS	*
SDP loaf volume (cm^3)[d]									
0.00%	1046	1058	1072	1069	1067	1068	1063	1048	1059
0.25%	1076	1077	1087	1061	1056	1068	1054	1088	1046
0.50%	1058	1092	1082	1057	1057	1071	1063	1067	1078
1.00%	1053	1145	1103	1062	1047	1094	1072	1059	1056
CR(DUN)[b]	31	26	29	34	ND	30	31	25	32
SIG(ANOVA)[c]	NS	***	NS	NS	NS	NS	NS	NS	NS

[a] Values represent mean of 3 blocks (1 firmness result per block).
[b] Critical range for significant difference ($p < 0.05$) between monoglyceride levels for Duncans multiple range test.
[c] Anova *F* value probability of significant level effect, * = 5%, ** = 1%, *** = 0.1%, NS = not significant.
[d] CSP loaf volume standard deviation = ±22; SDP loaf volume standard deviation = ±9.

Table 3
Effects of monoglyceride level on bread firmness averaged over storage time[a].

Level	12:0	14:0	16:0	18:0	22:0	18:1$_{cis}$	18:1$_{trans}$	18:2	18:3
CSP maximum force (N/m^2)[d]									
0.00%	6012	6551	5570	5948	5862	5773	5877	5863	6184
0.25%	6490	6557	5186	5692	5487	5339	5357	6336	6736
0.50%	7288	6674	5169	5086	5337	4889	4855	6743	6986
1.00%	7641	6498	4609	4679	5321	4457	4351	7122	6726
CR(DUN)[b]	583	523	375	562	430	445	333	614	399
SIG(ANOVA)[c]	***	NS	***	***	NS	***	***	***	**
SDP maximum force (N/m^2)[d]									
0.00%	6457	6141	6032	6093	6208	6068	6160	5951	6398
0.25%	7042	6251	5627	5994	5976	5547	5869	6374	6349
0.50%	7749	6439	5602	5638	5907	5627	5514	6682	6762
1.00%	7821	5916	5121	5279	5888	5307	4917	7072	6781
CR(DUN)[b]	651	460	341	404	996	369	362	712	554
SIG(ANOVA)[c]	***	NS	***	***	NS	**	***	*	NS

[a] Values represent mean of 3 blocks (1 firmness result per block).
[b] Critical range for significant difference ($p < 0.05$) between monoglyceride levels for Duncans multiple range test.
[c] Anova F value probability of significant level effect, * = 5%, ** = 1%, *** = 0.1%, NS = not significant.
[d] CSP maximum force standard deviation = ±277; SDP maximum force standard deviation = ±166.

Table 4
Effects of storage time on bread firmness averaged over monoglyceride level[a].

Day	12:0	14:0	16:0	18:0	22:0	18:1$_{cis}$	18:1$_{trans}$	18:2	18:3	CONT[d]
CSP maximum force (N/m^2)[e]										
1	4828	4883	3611	3945	3891	3714	3507	4879	4910	4163
2	6828	6769	5304	5391	5612	5090	5264	6288	7004	6173
3	8918	8058	6486	6717	7003	6540	6560	8383	8060	7544
CR(DUN)[b]	490	440	315	472	362	374	279	516	335	
SIG(ANOVA)[c]	***	***	***	***	***	***	***	***	***	
DAY 3–1	4090	3176	2875	2772	3113	2826	3053	3504	3150	3381
SDP maximum force (N/m^2)[e]										
1	5098	4252	3752	3997	3885	3875	3796	4755	4681	4086
2	7547	6366	5904	5935	5905	5763	5735	6759	6758	6382
3	9156	7942	7130	7321	8196	7234	7315	8056	8279	8034
CR(DUN)[b]	547	386	287	339	837	310	304	598	466	
SIG(ANOVA)[c]	***	***	***	***	***	***	***	***	***	
DAY 3–1	4058	3690	3378	3324	4311	3359	3519	3301	3598	3948

[a] Values represent mean of 3 blocks (1 firmness result per block).
[b] Critical range for significant difference ($p < 0.05$) between monoglyceride levels for Duncans multiple range test.
[c] Anova F value probability of significant level effect, * = 5%, ** = 1%, *** = 0.1%, NS = not significant.
[d] Average of 0% controls for all monoglyceride treatments.
[e] Average daily standard deviation: CSP day 1 = ±278, day 2 = ±319, day 3 = ±397; SDP day 1 = ±181, day 2 = ±170, day 3 = ±326.

duced bread firmness with increasing level. While both monopalmitate (C16:0) and monostearate (C18:0) resulted in significant increases in CSP loaf volume relative to the control (0%), there were not significant differences in loaf volume among the loaves with added monoglycerides. Therefore, differences in crumb softness would be attributable to the softening effect of monopalmitate and monostearate. At the 0.50% and 1.00% level, the latter appeared to be somewhat more effective than the former in reducing bread firmness relative to the control (0%).

The same trends were evident with the SDP. Increasing levels of the short chain C12:0 saturated and the C18:2 polyunsaturated monoglycerides significantly increased bread firmness while the C14:0, C22:0 and C18:3 monoglycerides had no significant impact. Significant reductions in bread firmness were obtained with the C16:0 and C18:0 saturated monoglycerides and both monounsaturated monoglycerides, with the C18:1 *trans* showing the largest reduction.

The superior performance of longer chain saturated monopalmitate (C16:0) and monostearate (C18:0) as crumb softeners shown in the data presented above is consistent with previous studies (Baldwin et al., 1965; Coppock et al., 1954; Doerfert, 1968; Lagendijk and Pennings, 1970; Inoue et al., 1995; Riisom et al., 1984). The equally superior performance of the monounsaturated monoglycerides, plus indications that the *trans*- sterioisomer form may offer the best overall performance, is in contrast to several previous studies showing that longer chain saturated monoglycerides are superior crumb softeners relative to unsaturated monoglycerides (Baldwin et al., 1965; Coppock et al., 1954; Doerfert, 1968; Lagendijk and Pennings, 1970). However, in the first three studies cited, this conclusion was based upon comparison of samples containing mixtures of saturated or unsaturated monoglycerides. Lagendijk and Pennings (1970), using purified monoglycerides, showed that monopalmitate (C16:0) was a superior bread softener relative to other saturated (C14:0, C18:0, C22:0 and C12:0) and unsaturated (C18:1 *cis* and C18:2) monoglycerides using a straight dough procedure. The *trans*- unsaturated monoglyceride (monoelaidate) was not included in that study. More recent studies have shown that *trans*- unsaturated monoelaidate was equally effective compared with saturated monopalmitate, as an anti-staling agent, while the *cis*- unsaturated monooleate (C18:1 *cis*) was less effective with both lean straight dough (Riisom et al., 1984) and SDP (Inoue et al., 1995) processing conditions.

The significant negative impact of the two polyunsaturated monoglycerides and the shorter chain (C12:0) monolaurate on crumb firmness during storage contrasts with studies by Lagendijk

and Pennings (1970) and Riisom et al. (1984). In both studies, monolinoleate (C18:2) was less effective than other monoglycerides but gave a softer crumb compared to the control, while in the former study, monolaurate was superior to the control. The reason for the contrasting results is not readily apparent although differences in process and/or the mode of addition of the monoglycerides (Riisom et al., 1984) may have influenced the response.

The effects of storage time on bread firmness averaged over the four levels of monoglyceride addition for the CSP and SDP are shown in Table 4. Data are also included for averages of the control (0%) samples across all monoglyceride treatments for each storage time. Increased storage time resulted in significant ($p < 0.001$) increases in crumb firmness for all monoglycerides with both processes. Many studies have demonstrated the strong impact of storage time on this parameter (Knightly, 1968, 1988; Maga, 1975; Stampfli and Nersten, 1995).

Differences among monoglyceride type were evident in both initial (after 1 day) crumb firmness values and in the rate at which crumb firmness increased with time. For both CSP and SDP, the lowest initial crumb firmness values were obtained with the C16:0 and C18:1 *trans* monoglycerides (Table 4). Further analysis of 1 day crumb firmness data showed that higher levels of these monoglycerides (0.5 and 1.0%) generally resulted in significant ($p < 0.05$) reductions in initial crumb firmness, relative to the control (Figs. 1 and 2). The C18:0, C22:0 and C18:1 *cis* monoglycerides also showed lower initial crumb firmness values relative to the average of the 1 day control samples for both processes. For the CSP, analysis of 1 day firmness data showed that higher levels of these three monoglycerides caused significant ($p < 0.05$) reductions in initial firmness values, with glycerol monostearate showing the largest effect. With the SDP, none of these monoglycerides had a significant impact on initial crumb firmness, relative to the controls (Fig. 2). The C14:0 monoglyceride showed initial crumb firmness values either slightly higher (SDP) or higher (CSP) than the 1 day control average (Table 4). Neither effect was significant (Figs. 1 and 2). The higher firmness with the CSP could be attributed to higher values obtained with the controls during the time when the C14:0 monoglyceride was tested (see Table 3). The remaining monoglycerides (C12:0, C18:2 and C18:3) showed initial firmness values higher than the 1 day control average for both baking processes. All of these higher values were significant ($p < 0.05$ or $p < 0.01$) based upon further analysis of 1 day firmness data (Figs. 1 and 2).

The rate at which firmness increased with storage time was estimated by calculating the change in crumb softness between the initial (1 day) and final (3 day) crumb firmness values (Table 4). For the CSP, the smallest changes were obtained with C16:0, C18:0 and the monounsaturated *cis*- monoglyceride. Slightly larger changes were evident with C14:0, C22:0, C18:1 *trans* and C18:3. The largest changes occurred with C18:2 and, in particular, the shortest chain saturated monoglyceride. With the SDP, the pattern of changes was somewhat different. The largest increase in firmness from 1 to 3 days storage occurred with the shortest and the longest chain saturated monoglycerides. The smallest changes occurred with the intermediate size saturated monoglycerides (C16:0 and C18:0), the *cis*- monounsaturated monoglyceride and C18:2 while slightly higher changes were obtained for C14:0, C18:1 *trans* and C18:3.

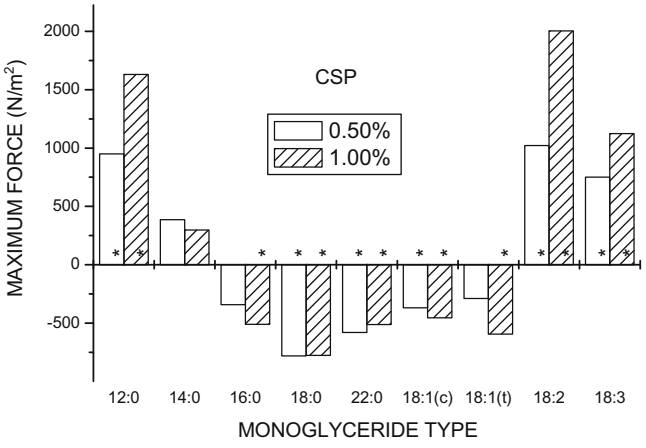

Fig. 1. Effects of monoglyceride type and level on CSP initial (1 day) crumb firmness. Treatments showing a significant difference ($p < 0.05$) from the 0% control are marked by an asterisk (*).

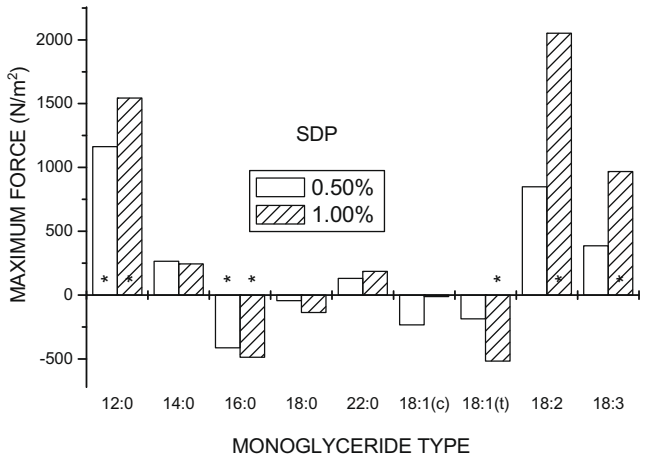

Fig. 2. Effects of monoglyceride type and level on SDP initial (1 day) crumb firmness. Treatments showing a significant difference ($p < 0.05$) from the 0% control are marked by an asterisk (*).

These data suggest that monoglyceride type and level can strongly influence both initial crumb firmness and the rate at which firmness increases with storage. Most previous studies indicate that monoglycerides act mainly by decreasing the rate of crumb firming during storage (Knightly, 1988). Their influence on initial crumb firmness has been less clear. Earlier studies, as reviewed by Knightly (1988), generally indicate that monoglycerides show little influence on this parameter. However, these studies were mainly limited to commercial or purified monoglycerides containing primarily glycerol monostearate. Other studies with a wider range of purified monoglycerides suggest that they can impart a reduction in initial crumb softness, dependent on the nature of the monoglyceride (Inoue et al., 1995; Riisom et al., 1984). In the former study, monopalmitate and monoelaidate were more effective than other unsaturated monoglycerides (C18:1*cis*, C18:2) using a lean straight dough procedure, while in the latter study, monosterate, monooleate and monoelaidate all appeared to be effective in reducing initial bread firmness using a SDP procedure. Unfortunately, the statistical significance of these effects was not determined.

Several workers (Baldwin et al., 1965; Bell et al., 1977) have pointed out that formulation and processing conditions appear to have an important impact upon monoglyceride performance although direct evidence was not provided in their studies. Our data also suggest that the baking process has a strong influence on the relative effect of individual monoglycerides on crumb firmness. This impact was particularly evident with monostearate, monooleate and monobehenate, all of which significantly reduced the initial crumb firmness of CSP bread but had no significant effect on SDP bread.

The results, in general, are consistent with the theory (Lagendijk and Pennings, 1970) that monoglycerides influence crumb softness based upon their ability to complex with amylose (and amylopec-

tin), thus reducing the rate of starch crystallisation (retrogradation). However, the increased crumb firmness, compared to the control, of monoglycerides (C12:0, and polyunsaturated monoglycerides) which show little or no binding to amylose or amylopectin (Lagendijk and Pennings, 1970), and differences in the relative impact of monoglycerides on initial crumb firmness versus the rate of firming suggests that other mechanisms (Stampfli and Nersten, 1995) may play an important role in the crumb firming process.

4. Conclusions

Mixing properties, bread quality and crumb firmness during bread storage were strongly influenced by the type and level of monoglyceride added to flour during bread processing. Polyunsaturated monoglycerides showed the greatest strengthening effects on dough properties based upon mixing properties. Most monoglycerides increased bread volume with the CSP but had little influence with the SDP. C16:0 and C18:0 saturated, as well as *cis*-and *trans*- monounsaturated monoglycerides, showed superior performance as crumb softeners. Bread process had a strong influence on the relative performance of these additives, suggesting that in commercial bakeries, the choice of monoglyceride may differ depending on the baking process.

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