Screw Configuration Effects on Macroscopic Characteristics of Extrudates Produced by Twin-screw Extrusion of Rice Flour

G. S. Choudhury and A. Gautam

ABSTRACT

The effects of 29 screw configurations on rice flour extrudates were investigated. The moisture content, screw speed and feed flow rate during all extrusion experiments were 15%, 400 rpm, and 12kg/h, respectively. Temperature profile in the 8 barrel sections from feed to die end were set at 0, 30, 30, 30, 70, 100, 150, and 150°C. Incorporation of kneading block (KB) and reverse screw element (RSE) in screw profiles significantly influenced apparent density, product expansion (radial, axial and overall), and breaking strength. Apparent density and overall expansion were functions of die temperature. KB was the best element for maximizing radial expansion. Product hardness (breaking strength) decreased with increasing radial expansion.

Key Words: screw configuration, macroscopic properties, rice flour, extrusion

INTRODUCTION

TWIN-SCREW EXTRUDERS ARE USED FOR PRODUCTION OF A WIDE variety of food products and extrudate characteristics from starchy and proteinaceous ingredients depend on physicochemical changes occurring during extrusion. Independent variables such as temperature, screw speed and throughput along with screw configuration and die geometry result in system parameters such as mechanical and thermal energy input, and residence time (Choudhury and Gogoi, 1995; Choudhury et al., 1997). Such intermediate parameters induce reactions that affect product attributes (Fig. 1). Twin-screw extruders are operational at very low feed moisture (6%) requiring no or minimum post-extrusion drying (Harper, 1989; Dziezak, 1989). In addition, they enable greater flexibility of operations to control product attributes by monitoring a desired time, temperature, and shear history because of the additional independent variable screw configuration.

The screw is the principal component of a food extruder. It accepts feed material at the inlet, conveys, mixes, and forces the material through the die at the discharge (Harper, 1981). Twin-screw extruders use segmented designs which provide flexibility to alter screw geometry. Extruder screws can be built from different types of conveying and mixing elements (kneading and reverse screw element). The kneading elements (KEs) are mild flow restricting elements, and individually have no conveying effect. However, they can be combined and oriented to cause static mixing, and/or weak forward or backward conveying. The reverse screw elements (RSEs) are characterized by a reverse flight pushing the material backward. The pitch, stagger angle, length, location of screw elements define a screw profile and are important parameters influencing extrudate characteristics during extrusion.

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Little has been published on the effects of screw configuration on macroscopic attributes of extrudates. Single-screw extrusion of corn starch with one or two mixing elements in a screw profile has been shown to influence expansion (Sokhey et al., 1994). Studies in our laboratory have shown that incorporation of KE and/or RSE in the profile increased expansion, but decreased bulk density and Warner-Bratzler shear stress (Gogoi et al. 1996a, b; Gautam et al. 1997; Choudhury et al., 1998; Choudhury and Gautam, 1998a). Results indicated that the screw configuration was a dominant variable that influenced macroscopic properties of the extrudate. The objective of this study was to investigate the effects of screw configuration, viz., the type, length, and position of screw elements, and spacing between them, on macroscopic characteristics of extrudates produced by twin-screw extrusion of rice flour.

MATERIALS & METHODS

Material

Medium grain rice flour, obtained from Pacific Grain Products, Inc. (Woodland, CA), was used as the main feed material for all experiments. The composition (Table 1) and particle size distribution (Table 2) of rice flour were provided by the supplier.

Extruder

All experiments were carried out using a co-rotating, intermeshing, self-wiping twin-screw extruder (Model BC 21, Clextral, Firminy Cedex, France). It was equipped with modular barrels, each 100 mm long, and bored with two 25 mm dia holes. The twin-screws had segmental screw elements, each 25 or 50 mm in length, so that kneading or reverse screw elements could be placed at a desired location along the length of a splined shaft. Thermal energy was provided by induction heaters mounted on 100 mm barrel sections. Length to di-

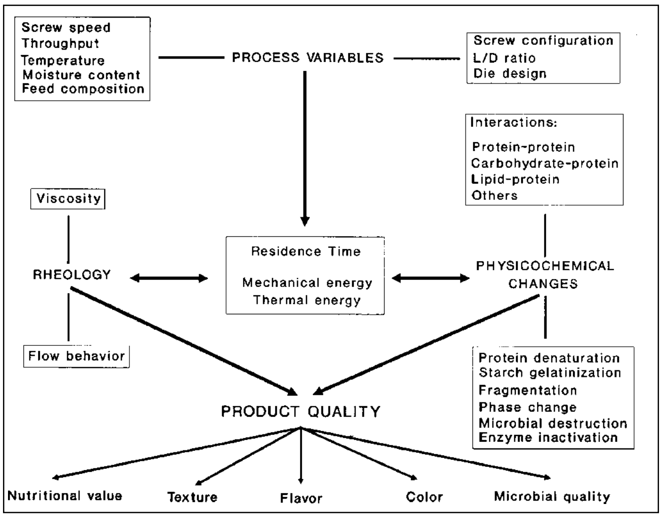

Fig. 1—Schematic of extrusion processing illustrating the effects of process variables on product attributes (Choudhury et al., 1977).

ameter (L/D) ratio was 32:1 and a 5 mm dia circular die was used. Material was fed into the extruder inlet port by a twin-screw (30 mm pitch) metering feeder, supplied by K-Tron Corporation (Pitman, NJ). Screw speed, material feed rate, barrel temperatures, % torque, die temperature, and power consumed by the induction heaters were monitored from a control panel.

Extrusion conditions

The extruder was divided into two zones: experimental and non-experimental zones. The length and pitch of conveying screw elements were kept constant in the 600 mm long non-experimental zone. The screw profile in this section from feed end was:

50/50/3   33.5/50/4   25/50/3   25/25/3   16.6/25/1

The numbers in each of the five sets represent pitch(mm)/length (mm)/number of elements.

A set of five kneading elements (KEs), each 5 mm long was used as a kneading block(KB). The KEs were oriented at 77 and 103° with each other to minimize the conveying capability in either forward or backward direction. Twenty-nine screw configurations were studied (Tables 3 and 4; Fig. 2). Configuration 1 had no mixing elements and is referred to as "conveying screw configuration." The remaining 28 screw configurations were built by placing either one (25 mm) or two (50 mm) KB(s) or RSE(s) at different locations in the 200 mm experimental zone. Position effects of mixing element(s) were evaluated by placing both 25 and 50 mm long mixing elements at 0, 50, 100, and 150 mm from the die (Configurations 2 to 9, and 16 to 23). Length and 0 mm spacing effects of mixing elements were studied by placing two (each 25 mm long) mixing elements at 0, 50, 100, and 150 mm from the die (Configurations 6 to 9 and 20-23). Another 12 screw profiles were developed by creating 25, 75, and 125 mm spacing between two (each 25 mm long) mixing elements (Configurations 10–15 and 24–29).

The K-Tron feeder was calibrated to determine the set point of the rotary feeder switch for rice flour to provide a flow rate of 12 kg/h for all experimental runs. Based on preliminary experiments and published data, screw speed and moisture content were fixed at 400 rpm and 15% (wb), respectively. Temperature profile in the 8 barrel sections from feed to die end were set at 0, 30, 30, 30, 70, 100, 150, and 150°C for all experiments. When extrusion operations were under steady state, indicated by temperature and torque, samples were collected and dried overnight under ambient conditions for analysis of extrudate characteristics. All results are averages of two extrusion runs.

Response variables

Response variables used to evaluate the effects of screw configuration on macroscopic attributes of extrudates were apparent and solid densities; radial, axial, and overall expansion; starch gelatinization; and textural attributes.

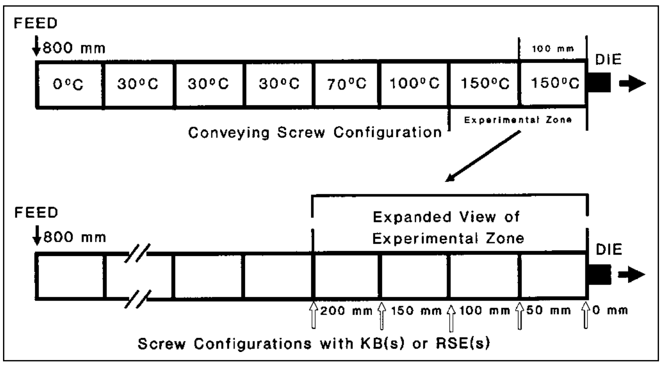

Fig. 2—Extruder layout for screw configuration study showing temperature profile and location of kneading block(s) or reverse screw element(s) in the experimental zone.

Table 1—Proximate composition of rice flour

Components	Mean ± SD
Moisture (%)	9.95 ± 0.08
Protein (%)[a]	5.85 ± 0.09
Fat (%)	0.56 ± 0.06
Ash (%)	0.47 ± 0.05
Crude fiber (%)	1.74 ± 0.07
Carbohydrate (%)[b]	81.43

[a]Protein = N*5.95.
[b]Carbohydrate by difference.

Table 2—Particle size distribution of rice flour.

	U.S. sieve no.	%
Retained on	50	0.9
	80	16.1
	100	7.5
	140	19.0
	200	18.5
Passed through	200	38.0

Densities

The apparent density ($\rho_{app.}$) was estimated by determining the mass and apparent volume of individual dry, cylindrical extruded rods (5–10 cm long). Apparent volume was calculated as the product of length and cross-section area of the extruded rods. True powder density (ρ_{true}) of the extrudates was determined by using Quantachrome multipycnometer following the procedure described by Chang (1988). The technique employs the Archimedes principle of fluid displacement to determine volume. The displaced fluid is a gas which can penetrate the finest spores. In this study helium was used because its

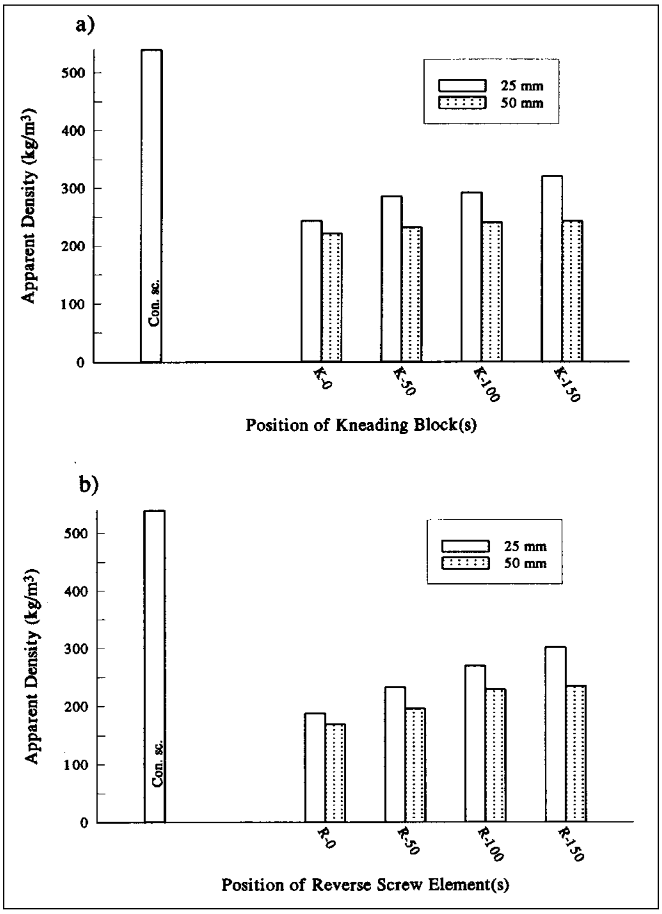

Fig. 3—Position and length effects of (a) kneading block and (b) reverse screw element on apparent density. K=kneading block (KB); R=reverse screw element (RSE).

Table 3—Screw configurations in the experimental zone (200 mm) showing location of conveying elements and kneading block(s)

Screw config. #	Location of KB from the die (mm)	Parameters evaluated	Profile of conveying elements and kneading block(s) (pitch/length/number or KB/length/number)				
1	—	—	16.6/50/2	16.6/25/4			
2	0	Position	16.6/50/2	16.6/25/3	[a]KB/25/1		
3	50		16.6/50/2	16.6/25/1	KB/25/1	16.6/25/2	
4	100		16.6/25/3	KB/25/1	16.6/50/2		
5	150		16.6/25/1	KB/25/1	16.6/25/2	16.6/50/2	
6	0 & 25	Length/ Spacing	16.6/50/2	16.6/25/2	KB/25/2		
7	50 & 75		16.6/50/2	KB/25/2	16.6/25/2		
8	100 & 125		16.6/25/2	KB/25/2	16.6/50/2		
9	150 & 175		KB/25/2	16.6/25/2	16.6/50/2		
10	0 & 50	Spacing	16.6/50/2	16.6/25/1	KB/25/1	16.6/25/1	KB/25/1
11	50 & 100		16.6/25/3	KB/25/1	16.6/25/1	KB/25/1	16.6/25/2
12	100 & 150		16.6/25/1	KB/25/1	16.6/25/1	KB/25/1	16.6/50/2
13	0 & 100		16.6/50/1	16.6/25/1	KB/25/1	16.6/25/3	KB/25/1
14	50 & 150		16.6/25/1	KB/25/1	16.6/25/3	KB/25/1	16.6/50/1
15	0 & 150		16.6/25/1	KB/25/1	16.6/50/1	16.6/25/3	KB/25/1

[a]KB=Kneading Block (25 mm long); KB=KE/77/1/5 KE/103/1/5 KE/77/1/5 KE/103/1/5 KE/77/1/5 (KE/Stagger angle (°)/No. of KE/length)

Table 4—Screw configurations in the experimental zone (200 mm) showing location of conveying and reverse screw element(s)

Screw config. # the die (mm)	Location of RSE from	Parameters evaluated	Profile of conveying and reverse screw element(s) (pitch/length/number)				
16	0	Position	16.6/50/2	16.6/25/3	[a]LH16.6/25/1		
17	50		16.6/50/2	16.6/25/1	LH16.6/25/1	16.6/25/2	
18	100		16.6/25/3	LH16.6/25/1	16.6/50/2		
19	150		16.6/25/1	LH16.6/25/1	16.6/25/2	16.6/50/2	
20	0 & 25	Length/ Spacing	16.6/50/2	16.6/25/2	LH16.6/25/2		
21	50 & 75		16.6/50/2	LH16.6/25/2	16.6/25/2		
22	100 & 125		16.6/25/2	LH16.6/25/2	16.6/50/2		
23	150 & 175		LH16.6/25/2	16.6/25/2	16.6/50/2		
24	0 & 50	Spacing	16.6/50/2	16.6/25/1	LH16.6/25/1	16.6/25/1	LH16.6/25/1
25	50 & 100		16.6/25/3	LH16.6/25/1	16.6/25/1	LH16.6/25/1	16.6/25/2
26	100 & 150		16.6/25/1	LH16.6/25/1	16.6/25/1	LH16.6/25/1	16.6/50/2
27	0 & 100		16.6/50/1	16.6/25/1	LH16.6/25/1	16.6/25/3	LH16.6/25/1
28	50 & 150		16.6/25/1	LH16.6/25/1	16.6/25/3	LH16.6/25/1	16.6/50/1
29	0 & 150		16.6/25/1	LH16.6/25/1	16.6/50/1	16.6/25/3	LH16.6/25/1

[a]LH = Left Hand screw, 25 mm long reverse screw element.

small atomic dimension assured penetration into crevices and pores approaching one Angstron (10^{-10}m).

Expansion ratios

The radial expansion ratio was measured as the ratio of the cross-section area of the extruded rods (A_{ex}) to that of the die (A_{die}) (Bhattacharya and Choudhury, 1994):

$$(ER)_{radial} = A_{ex}/A_{die} = (D_{ex})^2/(D_{die})^2 \quad (1)$$

where, D_{ex} is the diameter of the extruded product, and D_{die} is the diameter of the die

The overall expansion ratio was determined as a ratio of the apparent specific volume (v_{app}) to the true specific volume (v_{true}) of the extrudates:

$$(ER)_{overall} = V_{app}/V_{true} \quad (2)$$

The true volume was determined by Quantachrome multipycnometer.

Axial expansion of the extrudate was calculated from overall and radial expansion ratios using the equation:

$$(ER)_{axial} = (ER)_{overall}/(ER)_{radial} \quad (3)$$

Starch gelatinization by Differential Scanning Calorimetry (DSC)

Degree of starch gelatinization was evaluated from DSC endotherms (Yam et al., 1994). Unextruded rice flour and extrudates with different screw configurations were analyzed with a Perkin-Elmer DSC 7 differential scanning calorimeter (Perkin Elmer, Wilton, CT). Samples (10–20 mg) at 60% moisture were encapsulated in the stainless steel sample holders that could withstand high pressures. The DSC was purged with ultra pure N_2 gas at 206.8 kPa. The heating rate and scan range were 10°C/min and 40–115°C, respectively.

Breaking strength

The force required to cut the product into two pieces was an indicator of its hardness. It was determined as the maximum resistance by the sample during cutting in an Instron Universal Testing machine (Model No. 1000) with a Warner-Bratzler shear attachment. The stainless steel shear blade was 1.22 mm thick with a shear angle of 60°. Instron was operated at a cross-head speed of 500 mm/min; the full load scale was 100N. Single extruded cylindrical rods were placed in the Warner-Bratzler cell and cut into two pieces by the shear blade. Breaking strength was determined by dividing the maximum force to cut the product into two pieces by cross sectional area of the product (Chinnaswamy and Hanna, 1988).

Statistical analysis

Descriptive statistics and regression analysis were done using the Axum graphics and data analysis software (Trimetrix, 1992). Analysis of variance (ANOVA) was performed on all response variables by a statistical analysis software (SAS Institute, Inc., 1996) with significance of difference defined at $p \leq 0.05$.

RESULTS & DISCUSSION

Apparent density (AD) and True density (TD)

Type, length, and position, of elements affected the AD but interaction effects were not significant (Table 5). Extrudate from the conveying screw configuration had the highest apparent density (538 kg/m^3).

Incorporation of mixing elements lowered the AD considerably (Fig. 3). Extrudates obtained from screw profiles with KB had a higher AD than those obtained from screw profiles with RSE. AD decreased with a longer element, independent of position or type of element. For example, extrudate obtained with a 25 mm KB at 0 mm from the die had an AD of 242.89 kg/m^3. This reduced to 187.73 kg/m^3 when the KB was replaced by a RSE of similar length at the same position. But, a 50 mm long KB at the die produced an extrudate with an AD of 221.52 kg/m^3. AD increased systematically when a mixing element or a set of two mixing elements (with constant spacing) was moved farther from the die, irrespective of element type and length (Fig. 3 and 4). Larger spacing between two mixing elements increased the apparent density (Fig. 4).

According to Yacu (1995), higher die temperature caused more flashing at the die, which resulted in higher overall expansion and reduced density. We observed low AD values at high die temperature. A negative correlation between die temperature and apparent density (R=0.86 and F=73.27) was found (Fig. 5). Our results confirmed those of Bhattacharya and Hanna (1987), Grenus et al. (1992), and Bhattacharya and Choudhury (1994) that apparent density of extrudates decreased with increasing die temperature. The effects of type, length and position of the element on true density were not significant (Table 5). True density was not affected by screw configuration (Table 6). Values were similar to those of unextruded rice flour (1552.21±30.18 kg/m^3).

Table 5—Analysis of variance data for apparent and true densities of rice flour extrudates

		Mean Sum of Squares (MSS) and F-values for Density (kg/m^3)			
		Apparent Density		True Density	
Source	DF	MSS	F	MSS	F
Type (Typ)	1	8225.19	26.32**	3937.75	3.06
Length (Len)	1	16916.23	54.14**	235.53	0.18
Position (Pos)	3	7096.57	22.71**	2220.19	1.73
Typ × Len	3	227.10	0.73	1279.78	0.99
Typ × Pos	3	836.97	2.68	92.09	0.07
Pos × Len	3	920.41	2.95	1162.57	0.90
Typ × Len × Pos	1	17.16	0.05	1255.37	0.98
Error	16	312.46		1286.78	

**Highly significant at p≤0.005.

Radial expansion

The extent of reactions during extrusion affects product expansion. The expanded matrix in the extrudate was provided by the starch component. The expansion process can be described as nucleation in the die, extrudate swelling immediately beyond the die, followed by bubble growth and collapse (Kokini et al., 1991).

Extrudate from the conveying screw had a radial expansion ratio of 6.00 (Fig. 6). Incorporation of KB in the screw profile improved product expansion, irrespective of element length and position. However, this was not found with RSE (Fig. 6). Effects of type, length, and position of mixing elements and their interactions on radial expansion ratio were significant (Table 7). Screw profiles with KB produced more product expansion than those with RSE, irrespective of position and length. Generally, longer mixing elements reduced extrudate expansion, except when placed at (0 mm) the die (Fig. 6). The trend of radial expansion ratio with the position of element from the die was different for type and length of mixing element. When a KB (25 or 50 mm long) was moved farther from the die the radial expansion increased. Maximum radial expansion (10.65) was found with a 25 mm long KB at 150 mm from the die. However, when RSE (25 mm long) was moved farther from the die, the expansion first increased at 50 mm and than decreased continuously. A systematic decrease in radial expansion was observed by moving 50 mm long RSE farther from the die (Fig. 6b).

The radial expansion ratio decreased considerably when two RSEs with constant spacing were moved farther from the die (Fig. 7b).

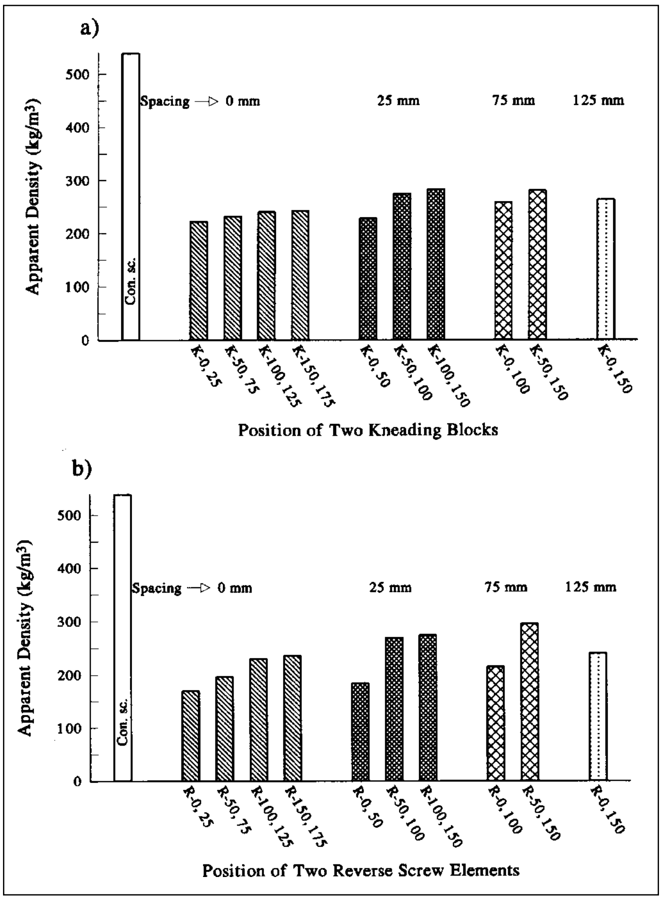

Fig. 4—Position and spacing effects of (a) two kneading blocks and (b) two reverse screw elements on apparent density. K=kneading block (KB); R=reverse screw element (RSE).

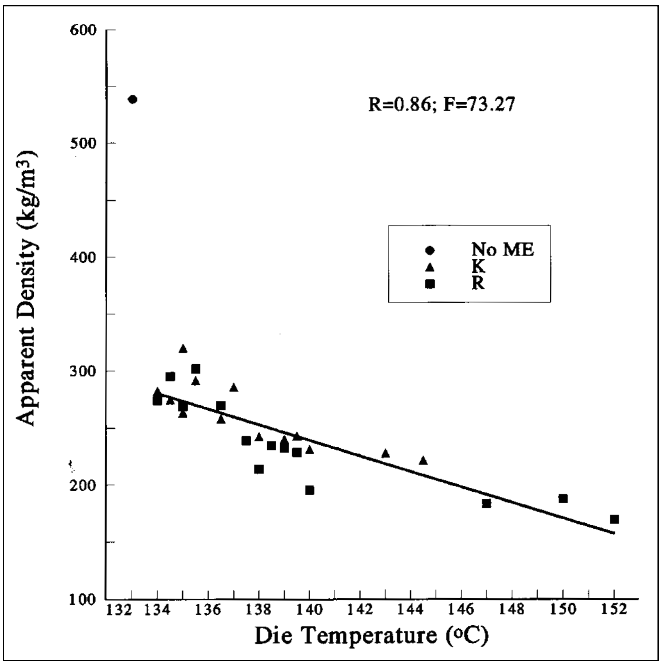

Fig. 5—Relationship between apparent density and die temperature. No ME=no mixing element; K=kneading block (KB); R=reverse screw element (RSE).

Table 6—Effect of screw configuration with kneading block (KB) and reverse screw element (RSE) on true density (TD) of rice flour extrudates

Location of KB(s) or RSE(s) from the die (mm)	Parameters evaluated	TD (kg/m^3) in presence of KB(s)	TD (kg/m^3) in presence of RSE(s)
None	—	1452.55 ± 30.18	1452.55 ± 30.18
0	Position	1479.26 ± 34.31	1481.15 ± 48.46
50		1450.00 ± 47.38	1466.54 ± 37.71
100		1445.60 ± 52.33	1445.78 ± 37.87
150		1479.26 ± 16.41	1425.50 ± 36.42
0 & 25	Length/Spacing	1482.58 ± 51.22	1450.92 ± 27.89
50 & 75		1498.60 ± 17.98	1439.25 ± 17.58
100 & 125		1482.41 ± 37.07	1444.00 ± 23.76
150 & 175		1422.50 ± 18.78	1412.50 ± 31.54
0 & 50	Spacing	1497.29 ± 37.61	1432.20 ± 36.85
50 & 100		1442.56 ± 27.70	1432.20 ± 36.48
100 & 150		1412.56 ± 42.76	1421.23 ± 32.12
0 & 100		1475.10 ± 36.20	1444.10 ± 33.52
50 & 150		1423.45 ± 31.91	1423.44 ± 26.50
0 & 150		1430.90 ± 45.11	1412.50 ± 15.70

Table 7—Analysis of variance data for expansion ratios of rice flour extrudates

		Mean Sum of Squares (MSS) and F-values for Expansion Ratios					
		Radial Expansion Ratio		Overall Expansion Ratio		Axial Expansion Ratio	
Source	DF	MSS	F	MSS	F	MSS	F
Type (Typ)	1	93.06	1585.17**	5.61	41.14**	30.27	28.89**
Length (Len)	1	6.83	116.41**	8.63	63.33**	77.54	74.01**
Position (Pos)	3	4.29	73.04**	6.04	44.31**	39.35	37.56**
Typ × Len	3	0.56	9.53*	0.05	0.40	1.78	1.70
Typ × Pos	3	6.80	115.91**	1.32	9.66*	4.50	4.30
Pos × Len	3	3.64	62.00**	0.16	1.19	3.86	3.68
Typ × Len × Pos	1	0.86	14.64**	0.04	0.26	0.40	0.38
Error	16	0.06		0.14		1.05	

**Highly significant at $p \leq 0.005$.
*Significant at at $p \leq 0.05$

Also, positioning the first RSE at 50 or 100 mm from the die, and then moving the second RSE farther from the die, caused a considerable decrease in expansion. However, with KBs the reduction in expansion was marginal for similar spacing (Fig. 7a).

Extrudate expansion is influenced by degree of gelatinization (Mercier and Feillet, 1975; Chinnaswamy and Bhattacharya, 1983, 1984; Cai and Diosady, 1993), starch breakdown (Gomez and Aguilera, 1983, 1984; Kirby et al., 1988; Cai and Diosady, 1993), and amylose content (Chinnaswamy and Hanna, 1990). DSC scan has shown that starch in extrudates obtained with all screw configurations was fully gelatinized.

Effect of specific mechanical energy (SME) input (Choudhury and Gautam, 1998b) on radial expansion ratio was less prominent for configurations with KB(s) than those with RSE(s) (Fig. 8). In general, the expansion ratio remained above 8.00 with all positions, lengths, and spacings of KBs, although there was an increase in SME input (Fig. 8). Incorporation of KB might have provided optimum mechanical and thermal energy input resulting in more expansion. This may be due to an increase in straight chain polymer (amylose) content as a result of amylopectin breakdown during extrusion. Initial amylose content of the rice flour was 20–25%. This concentration might have increased to an optimum (≈50%) by incorporation of KB. Chin-

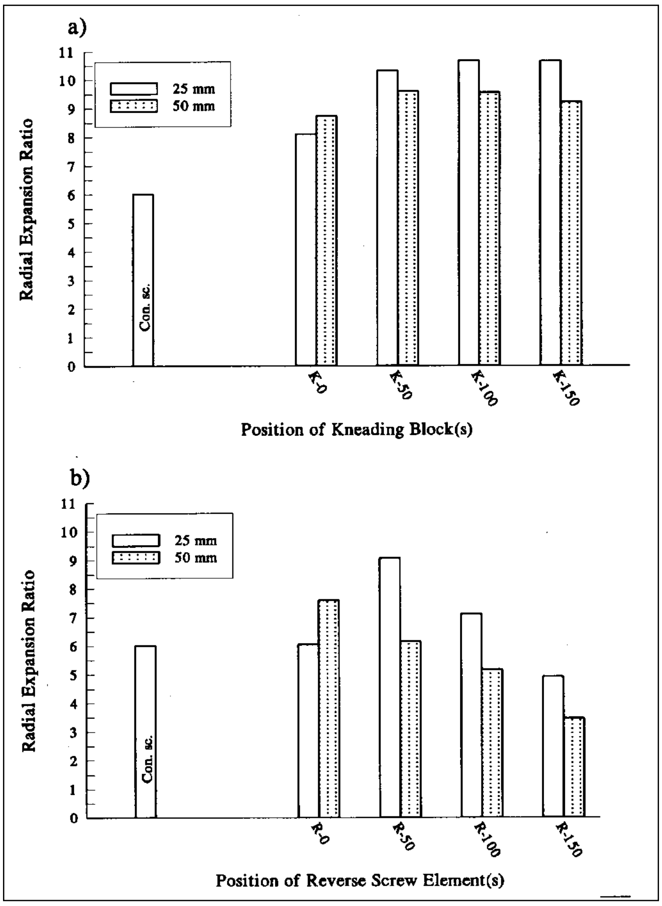

Fig. 6—Position and length effects of (a) kneading block and (b) reverse screw element on radial expansion ratio. K=kneading block (KB); R=reverse screw element (RSE).

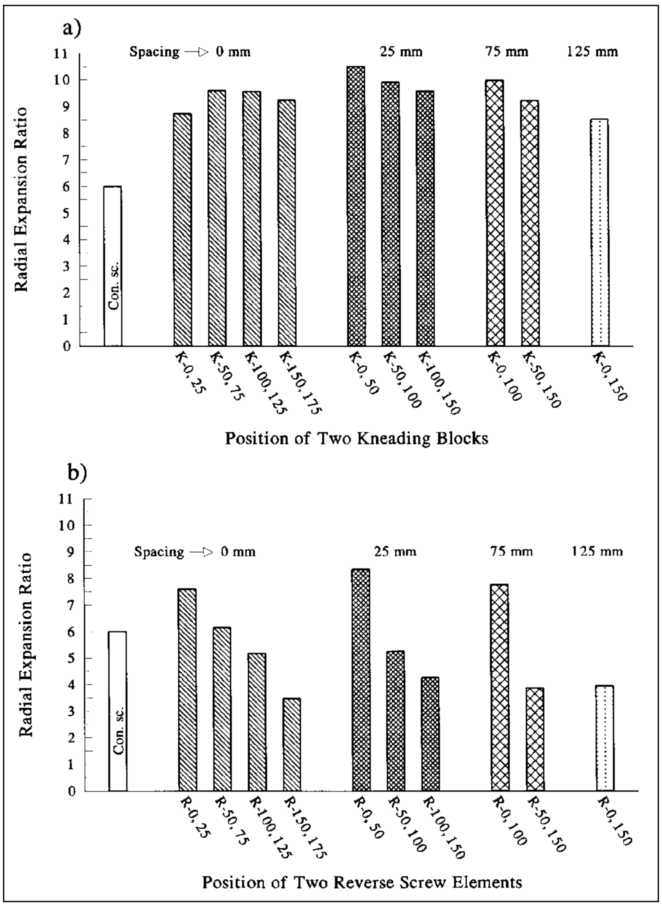

Fig. 7—Position and spacing effects of (a) two kneading blocks and (b) two reverse screw elements on radial expansion ratio. K=kneading block (KB); R=reverse screw element (RSE).

naswamy and Hanna (1990) reported maximum expansion during extrusion of corn starch with 50% amylose.

Screw profiles with RSE had a higher SME input (Choudhury and Gautam, 1998a, b) and produced more low molecular weight fragments (Gautam and Choudhury, 1998) compared to those with KB. Increased distance from the die, longer element, and wider spacing between two elements also produced low molecular weight compounds. Very severe screw configuration (with SME input $>$145 kJ/kg) resulted in radial expansion ratio $<$ 5.0 (Fig. 8). This reduction in expansion may have been due to fragmentation of starch to dextrins. Similar reduced expansion due to dextrinization of starch was reported by Gomez and Aguilera (1983, 1984), Colonna et al. (1984), and Davidson et al. (1984).

Table 8—Analysis of variance data for breaking strength of rice flour extrudates

		Mean Sum of Squares (MSS) and F-values for Breaking strength (MPa)	
Source	DF	MSS	F
Type (Typ)	1	0.4383	487.00**
Length (Len)	1	0.0934	103.78**
Position (Pos)	3	0.0534	59.33**
Typ × Len	3	0.0756	84.00**
Typ × Pos	3	0.0745	82.77**
Pos × Len	3	0.0324	36.00**
Typ × Len × Pos	1	0.0290	32.22**
Error	16	0.0009	

**Highly significant at $p \leq 0.005$

Axial expansion

Effect of screw configuration on axial expansion was determined (Fig. 9,10). The trend was opposite to that on radial expansion. We observed shrinkage along the axial direction for some screw configurations. Axial expansion of $<$1 has been reported (Hanna et al., 1997). The effects of type, position, and length of mixing elements and their interactions on axial expansion were significant (Table 7).

Overall expansion

The effect of screw configuration on overall expansion ratio showed the opposite trend to that on apparent density. Type, length and position of screw elements affected the overall expansion ratio, but interaction effects were not significant (Table 7). An overall expansion ratio of 2.88 was obtained with a conveying screw configuration. Incorporation of mixing elements increased the overall expansion ratio considerably (Fig. 11). Screw profiles with RSE produced extrudates with higher overall expansion than those with KB at all positions and for both lengths. However, at a given position, a larger overall expansion ratio was observed with the longer element. For example, the values of overall expansion ratio obtained using a 25 mm KB and RSE positioned at 0 mm from the die were 6.09 and 7.90, respectively. But, 50 mm long KB and RSE at the same position produced extrudates with values of 6.69 and 8.56, respectively. Increased spacing between two elements and moving the elements (with constant spacing) farther from the die decreased the overall expansion ratio (Fig. 12).

Yacu (1995) has shown that overall expansion ratio and die temperature were directly related. In our results, a good correlation between die temperature and overall expansion (R=0.89 and F=107.68) was observed (Fig. 13a). When die temperature was low, less flashing occurred at the die resulting in less overall expansion. A negative correlation between apparent density and overall expansion (R=0.97 and F=522.78) was observed (Fig. 13b).

Breaking strength

Screw configuration affected the breaking strength in an opposite

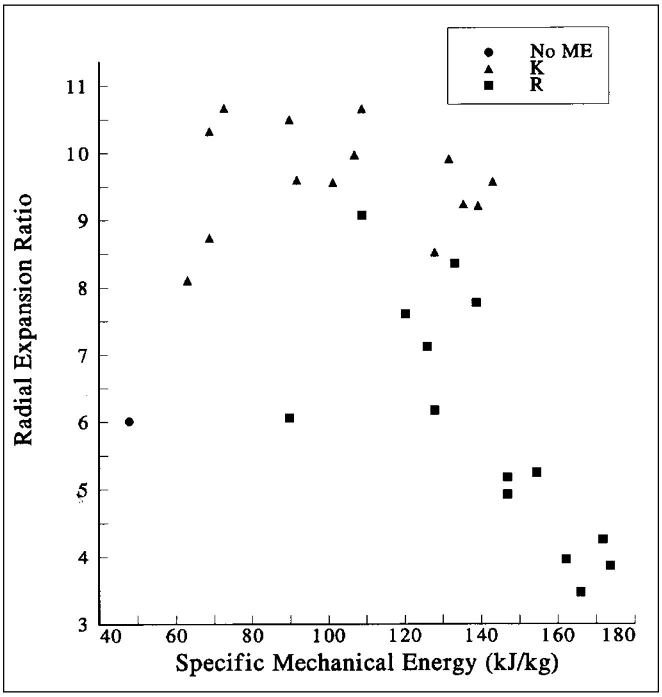

Fig. 8—Influence of mixing elements on radial expansion ratio and specific mechanical energy. No ME=no mixing element; K=kneading block (KB); R=reverse screw element (RSE).

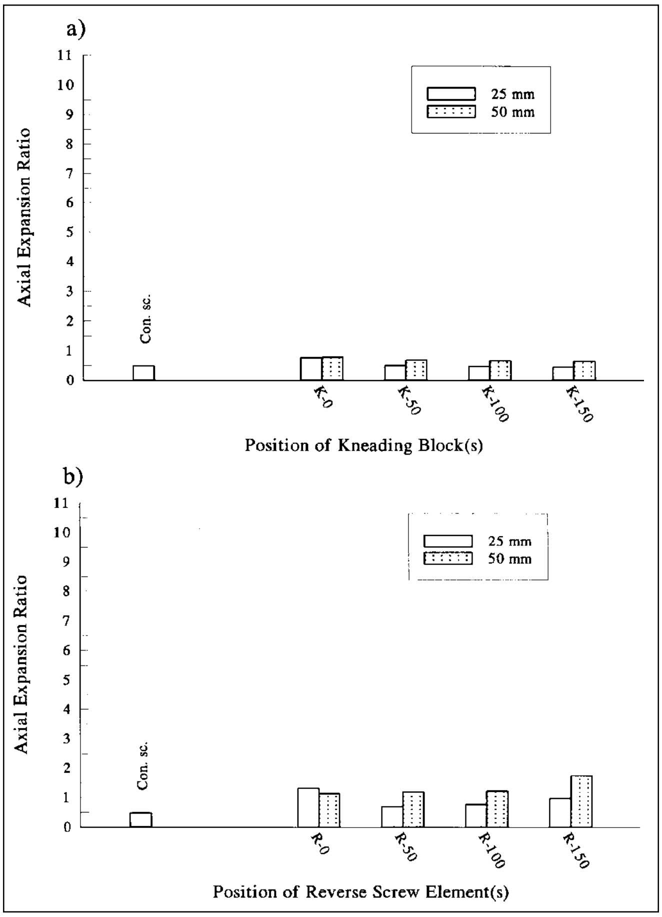

Fig. 9—Position and length effects of (a) kneading block and (b) reverse screw element on axial expansion ratio. K=kneading block (KB); R=reverse screw element (RSE).

fashion to that of radial expansion ratio (Fig. 14 and 15). Table 8 shows that the type, length, and position of mixing elements, and their interactions affected the breaking strength. Conveying screw produced an extrudate with a high breaking strength (0.42 MPa). In all cases, incorporation of KB(s) lowered the breaking strength (Fig. 14a and 15a). Inclusion of RSE(s) of different lengths at various positions and with different spacings had mixed effects on breaking strength (Fig.. 14b and 15b). Screw profiles with KB always produced extrudates with lower breaking strength than those with RSE. Longer mixing elements increased the breaking strength, except when placed at 0 mm from the die (Fig. 14). Longer RSE produced extrudates with very high breaking strength (>0.5 MPa). Similarly, when the first RSE was positioned at 0 or 50 mm from the die and the second RSE was moved away from the die, a considerable increase in breaking strength resulted.

The higher the radial expansion, the lower was the reported shear stress (Owusu-Ansah et al., 1984; Bhattacharya and Hanna, 1987; Chinnaswamy and Hanna, 1988) and our results confirmed those findings. A negative correlation between the radial expansion ratio and breaking strength (R=0.91 and F=122.27) was observed (Fig. 16). Less peak force was required to cut a more expanded product into two pieces with a Warner Bratzler shear cell. For example, a peak force of about 50N was needed to break a product obtained using a conveying screw configuration (radial expansion ratio of ~6.0). However, a peak force of only 32N was required to break a product with expansion ratio of 10.65 (obtained using a screw profile with a KB at 150 mm from the die).

Breaking strength did not correlate well with either overall expansion ratio (Fig. 17a) or SME (Fig. 17b). Incorporation of KBs in

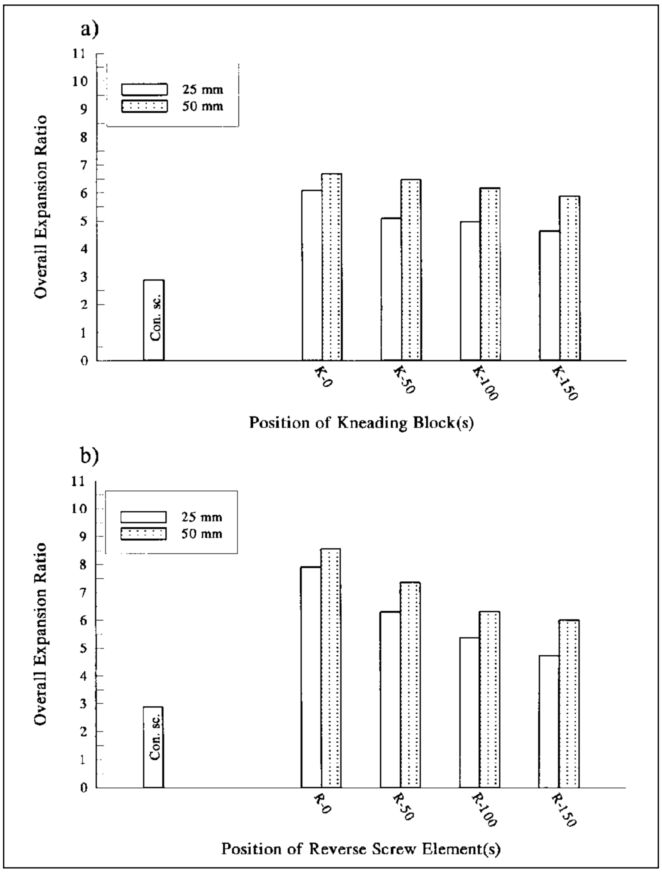

Fig. 11—Position and length effects of (a) kneading block and (B) reverse screw element on overall expansion ratio. K-kneading block (KB); R=reverse screw element (RSE).

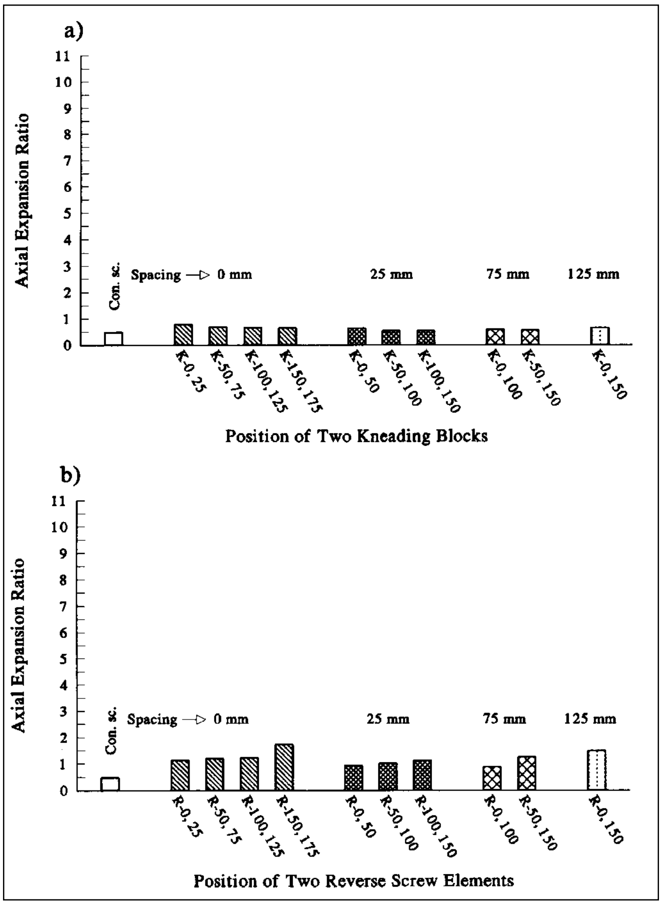

Fig. 10—Position and spacing effects of (a) two kneading blocks and (b) two reverse screw elements on axial expansion ratio. K=kneading block (KB); R=reverse screw element (RSE).

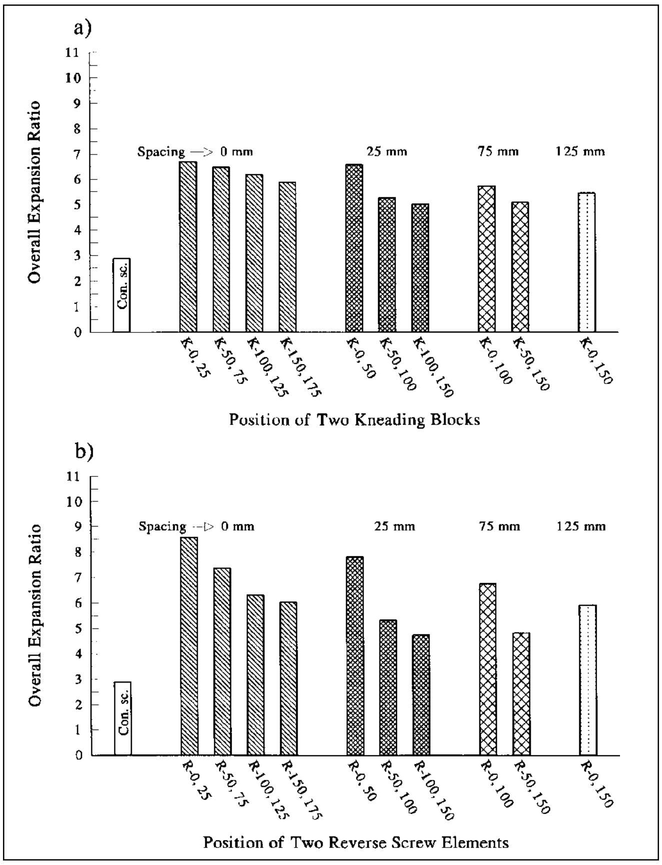

Fig. 12—Position and spacing effects of (a) two kneading block and (b) two reverse screw elements on overall expansion ratio. K=kneading block (KB); R=reverse screw element (RSE).

the screw profile yielded extrudates with low breaking strength (<0.35 MPa), although there was an increase in SME input (Fig. 17b). But screw profiles with RSE produced extrudates that showed increasing breaking strength with an increase in SME input.

CONCLUSIONS

SCREW CONFIGURATION WAS A DOMINANT VARIABLE AFFECTING macroscopic characteristics of extrudates. The type, length, position, of mixing elements and spacing between elements affected all macroscopic properties except true density. Apparent density increased systematically when mixing elements were moved farther from the die and with wider spacing between elements, irrespective of element type or length. However, apparent density decreased with a longer element. Screw configuration effect on overall expansion was opposite to that on apparent density. An increase in die temperature, as a result of screw configuration effect, decreased apparent density and increased overall expansion. The relationships in both cases were linear. Radial expansion was higher for screw profiles with KB than those with RSE, irrespective of element length, position, or spacing. For KB and RSE, maximum expansion occurred when the element was 150 and 50 mm from the die end, respectively. Screw configuration effect on axial expansion was opposite of radial expansion. Textural attributes of extrudates were affected by screw configuration. Screw profiles with KB always produced extrudates with lower breaking strength than those with RSE. Breaking strength was negatively correlated with radial expansion. Mild to very severe processing can be induced by manipulation of screw configuration with mixing elements. Desired product expansion and textural attributes can be achieved by appropriate selection of type, location, and length of mixing elements.

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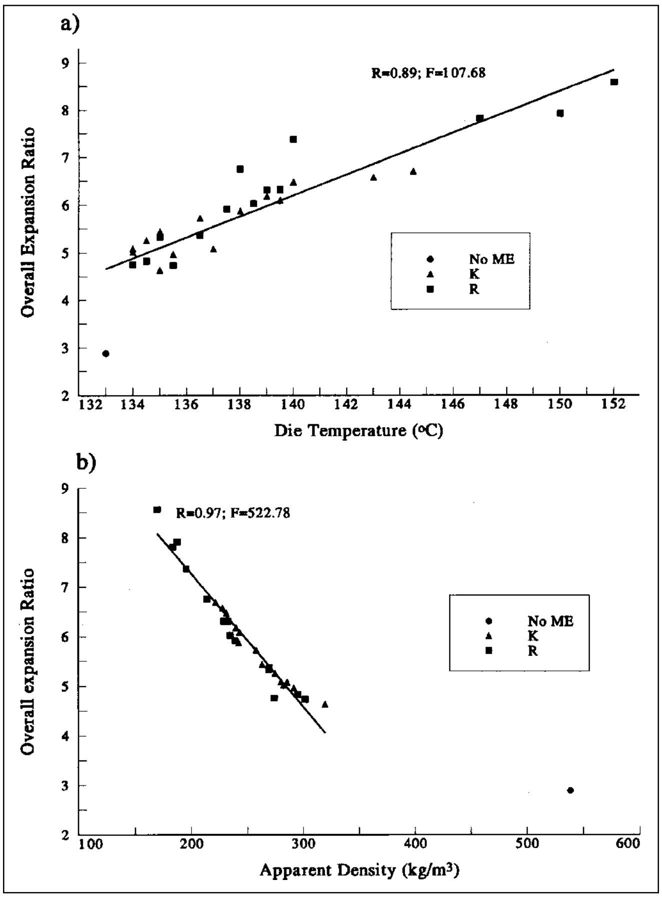

Fig. 13—Relationship between (a) Overall expansion and die temperature (b) apparant density and overall expansion. No ME=No Mixing element; K=Kneading Block (KB); R=Reverse Screw Element (RSE).

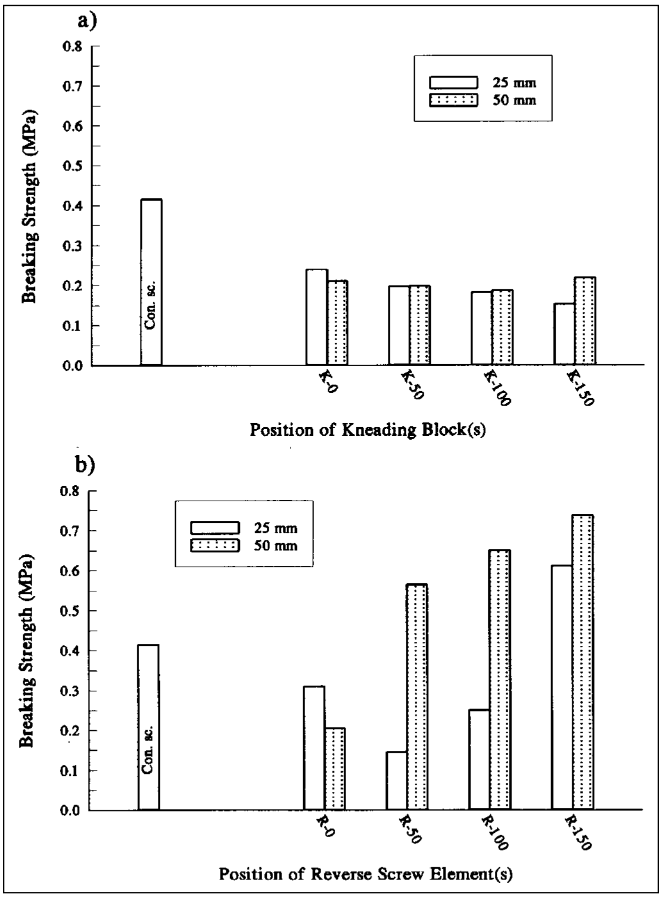

Fig. 14—Position and length effects of (a) kneading block and (b) reverse screw element on breaking strength. K=Kneading Block (KB); R=Reverse Screw Element (RSE).

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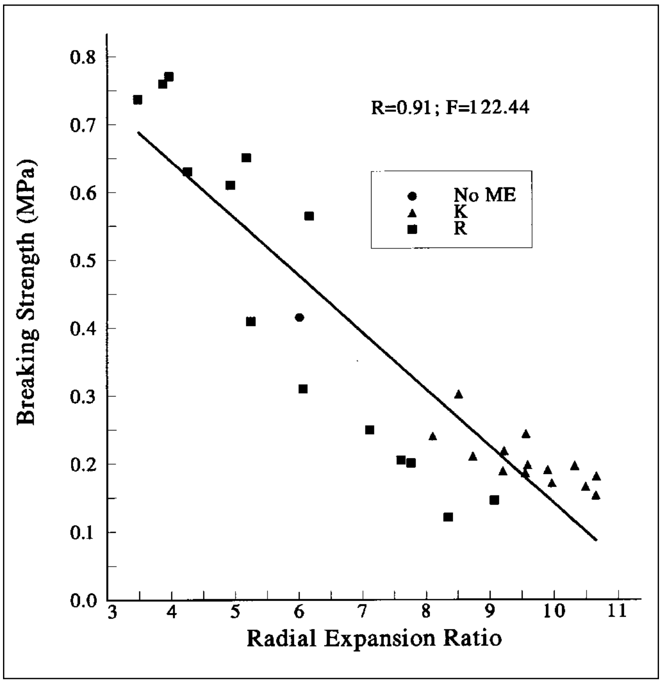

Fig. 16—Relationship between breaking strength and radial expansion ratio. No ME=No Mixing element; K=Kneading Block (KB); R=Reverse Screw Element (RSE).

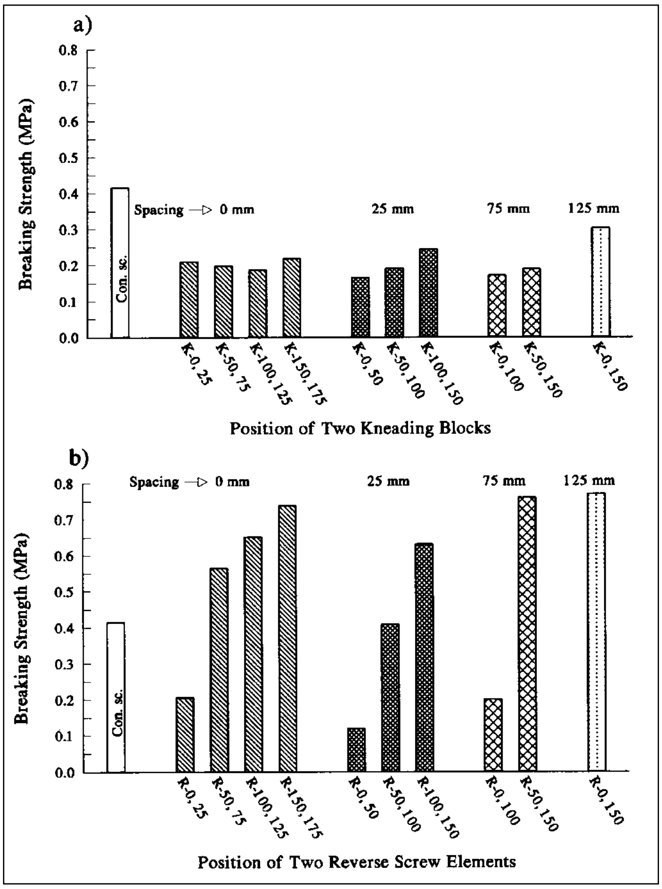

Fig. 15—Position and spacing effects of (a) two kneading blocks and (b) two reverse screw element on breaking strength. K=Kneading Block (KB); R=Reverse Screw Element (RSE).

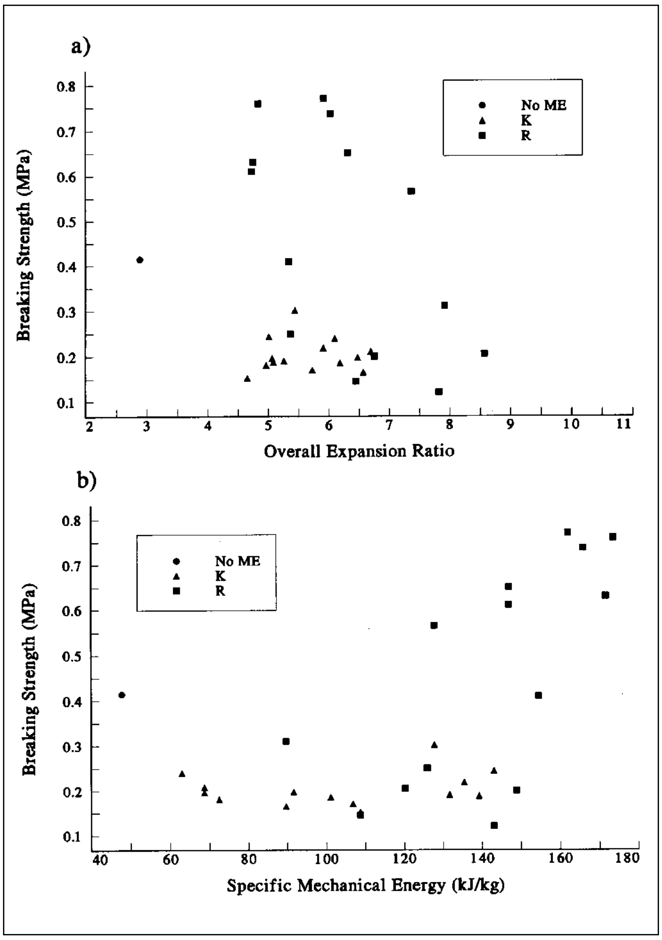

Fig. 17—Influence of mixing elements on (a) breaking strength and overall expansion, and (b) breaking strength and specific mechanical energy. No ME=No Mixing element; K=Kneading Block (KB); R=Reverse Screw Element (RSE).