Particle size distribution and chemical composition of total mixed rations for dairy cattle: Water addition and feed sampling effects

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ABSTRACT

Four dairy farms were used to determine the effects of water addition to diets and sample collection location on the particle size distribution and chemical composition of total mixed rations (TMR). Samples were collected weekly from the mixing wagon and from 3 locations in the feed bunk (top, middle, and bottom) for 5 mo (April, May, July, August, and October). Samples were partially dried to determine the effect of moisture on particle size distribution. Particle size distribution was measured using the Penn State Particle Size Separator. Crude protein, neutral detergent fiber, and acid detergent fiber contents were also analyzed. Particle fractions 19 to 8, 8 to 1.18, and <1.18 mm were judged adequate in all TMR for rumen function and milk yield; however, the percentage of material >19 mm was greater than recommended for TMR, according to the guidelines of Cooperative Extension of Pennsylvania State University. The particle size distribution in April differed from that in October, but intermediate months (May, July, and August) had similar particle size distributions. Samples from the bottom of the feed bunk had the highest percentage of particles retained on the 19-mm sieve. Samples from the top and middle of the feed bunk were similar to that from the mixing wagon. Higher percentages of particles were retained on >19, 19 to 8, and 8 to 1.18 mm sieves for wet than dried samples. The reverse was found for particles passing the 1.18-mm sieve. Mean particle size was higher for wet than dried samples. The crude protein, neutral detergent fiber, and acid detergent fiber contents of TMR varied with month of sampling (18–21, 40–57, and 21–34%, respectively) but were within recommended ranges for high-yielding dairy cows. Analyses of TMR particle size distributions are useful for proper feed bunk management and formulation of diets that maintain rumen function and maximize milk produc-

tion and quality. Water addition may help reduce dust associated with feeding TMR.

Key words: dairy cow, ration, particle size, feed bunk

INTRODUCTION

Dairy cows with high genetic potential for milk production require high-energy rations to meet nutrient needs. Such diets may cause low intake at the beginning of lactation, and negative associative effects between high energy and finely chopped forages in the diet can be present. Alteration of the physical nature of fiber in forage may also reduce rumination stimuli and saliva flow (Murphy and Zhu, 1996). Dairy cattle diets formulated to supply a minimum of 21% NDF from forage sources without consideration of NDF from concentrates reduce DMI, milk yield, and fat in milk and cause health problems such as laminitis, acidosis, ketosis, and displaced abomasum (Beauchemin et al., 1994). The feed industry needs methodology to properly evaluate the effective fiber content of diets that allow maintenance of high milk yield and optimal ruminal health. Among these methodologies is the evaluation of particle size, which is a test to identify the part of fiber in diets that is effective in stimulating rumination and saliva production. In principle, particle size analysis of a diet is similar to analysis of CP or other nutrient analyses. Particle size distributions and mixing homogeneity can be evaluated together when the aim is to have a homogeneously mixed ration that will have a positive effect on the productive performance of high-yielding dairy cows (Grant et al., 1990).

The measurement of the particle size distribution is another tool to maximize DMI and milk yield of dairy cows (Righi et al., 2007). Also, smaller particle size (<1.18 mm) improved digestion and increased DMI, milk yield, and milk casein and was without effect on milk fat. Zebeli et al. (2008) concluded that increasing the fraction of particles between 8 and 19 mm, and probably the fraction <8 mm, by decreasing theoretical particle lengths of grass silage does not adversely

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affect rumen conditions and can be beneficial in terms of optimizing concentration and activity of ruminal microbiota in high-yielding dairy cows.

Physically effective NDF (**peNDF**) measures the physical characteristics of fiber by accounting for particle length and NDF content, which promotes chewing and the flow of salivary buffers to the rumen (Mertens, 1997). The term peNDF is used in diet formulation to provide fiber of adequate particle length to reduce acidosis. Yang and Beauchemin (2007) found that the intake of dietary peNDF is a good indicator of ruminal pH status of dairy cows and concluded that increasing the proportion of forage in the diet helps prevent ruminal acidosis through increased chewing time, a change in meal patterns, and decreased ruminal acid production. Increasing forage particle size increases ruminal pH, but in low-forage diets increased forage particle size does not completely alleviate subacute acidosis because the fermentability of the diet is high and changes in chewing activity are marginal.

Information is lacking on the effects of water addition during mixing or sample collection location from the feed bunk on particle size distributions of TMR. Our objective was to evaluate the effects of these factors on TMR particle size distributions using the Penn State Particle Separator.

MATERIALS AND METHODS

Location

The experiment was conducted in Delicias, Chihuahua, Mexico. The area is located at 28°11' N and 105°28' W at an altitude of 1,165 m. Annual mean rainfall is 319.8 mm, and the climate is semi-arid (Álvarez, 1980).

Sample Collection

Feed samples came from TMR fed on 4 similar dairy farms (Holstein cows averaged a total lactation yield through 305 DIM of 9,100 kg) that use modern management practices (Table 1). Rations were prepared in feed mixer wagons of 6,000-kg capacity, 3 horizontal augers, and a mixing time averaging 15 min, depending on the time required for delivering the feed through the bunk. During mixing, alfalfa hay was followed by corn silage, cottonseed, concentrate mix, and then water. The amount of water added was different on each farm and was based solely on a management decision of each dairy.

Samples of TMR (about 3 kg) were collected at feeding time but before cows began to consume feed. Samples were collected from the mixer wagon and feed

Table 1. Total mixed rations by dairy farm and through 5 mo¹ of the year (% on DM basis)

Ingredient	Dairy farm 1					Dairy farm 2					Dairy farm 3					Dairy farm 4				
	A	M	J	G	O	A	M	J	G	O	A	M	J	G	O	A	M	J	G	O
Alfalfa hay	19	13	13	13	13	5	12	12	12	15	5	17	17	15	18	14	14	8	8	8
Fresh alfalfa		4	4	4	4						2	5	5	5	4					
Corn silage	11	9	9	9	9	18	17	17	17	11	12	7	7	7	9	20	20	11	12	12
Alfalfa silage																		5	4	6
Concentrate	25	22	23	23	23	16	28	28	30	32	28	23	22	22	22	20	17	23	23	22
Cottonseed	6	5	5	5	5						5	4	5	5	5		3	3	3	3
Triticale							4				2									
Water added, % as-fed basis	12	11	11	11	11	6	6	6	6	14	5	8	9	10	9	6	7	18	18	16
Water added, L/cow per day	3.0	2.8	2.8	2.8	2.8	1.5	1.5	1.5	1.5	3.5	1.3	2.0	2.3	2.5	2.3	1.5	1.8	4.5	4.5	4.0
Moisture content before water addition	36	44	44	44	44	41	41	41	40	37	38	41	42	43	41	45	45	45	46	46
Moisture content after water addition	48	55	55	55	55	47	47	47	46	51	43	49	51	53	50	51	52	63	64	62
Forage:concentrate ratio	49:51	49:51	49:51	49:51	49:51	59:41	54:46	51:49	49:51	45:55	40:60	52:48	53:47	51:49	54:46	63:37	63:37	49:51	50:50	52:48

¹A = April, M = May, J = July, G = August, and O = October.

Table 2. Neutral detergent fiber content of TMR¹ through 5 mo of the year (% DM basis)

Dairy farm	Month					SD
	April	May	July	August	October	
DF1	40.7 ^d	56.9 ^a	51.0 ^b	46.3 ^c	46.1 ^c	0.95
DF2	46.4 ^b	43.7 ^c	42.3 ^c	42.2 ^c	55.9 ^a	0.95
DF3	39.5 ^c	46.8 ^b	57.1 ^a	40.3 ^c	47.5 ^b	0.95
DF4	45.8 ^c	39.9 ^d	48.8 ^b	47.4 ^{bc}	52.5 ^a	0.95

^{a-d}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

bunk (top, middle, and bottom). Samples were obtained weekly from each farm; therefore, 4 samples contributed to monthly means.

Particle Size Determination

Particle separations were made using the Penn State Particle Separator: the 19-mm plastic sieve, followed by 8-mm and 1.18-mm steel sieves, and then the plastic bottom pan. A sample (800 g) was placed on the 19-mm sieve. The sieving procedure involved 10 horizontal, 17-cm movements perpendicular to each side of the box, with a total of 40 movements. Screen rotation prevented particle agglomeration. Each sample was analyzed in duplicate. Amounts of sample on each sieve were expressed as a percentage of sample size. It was assumed that samples had a logarithmic-normal distribution with a geometric mean and standard deviation, estimated according to the procedures of ASAE (2001).

To determine the effect of water addition to TMR on particle size distributions, as-fed samples were collected and subjected to particle size separation using the Penn State Particle Separator. Then, to measure the effects of adding water, samples were dried at 55°C until constant weight was attained and particle size distributions were determined again.

Table 3. Crude protein content of TMR¹ through 5 mo of the year (% DM basis)

Dairy farm	Month					SD
	April	May	July	August	October	
DF1	17.8 ^b	18.7 ^a	18.9 ^a	17.7 ^b	18.9 ^a	0.31
DF2	19.1 ^{ab}	18.2 ^c	18.1 ^c	18.7 ^{bc}	19.6 ^a	0.31
DF3	19.6 ^{bc}	19.4 ^c	20.3 ^{ab}	19.5 ^{bc}	20.9 ^a	0.31
DF4	18.1 ^{bc}	17.7 ^c	18.8 ^b	17.9 ^c	20 ^a	0.31

^{a-c}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

Table 4. Acid detergent fiber content of TMR¹ through 5 mo of the year (% DM basis)

Dairy farm	Month					SD
	April	May	July	August	October	
DF1	28.2 ^a	26.0 ^b	25.0 ^b	26.7 ^{ab}	25.5 ^b	0.67
DF2	27.5 ^a	27.3 ^a	24.8 ^b	21.3 ^c	25.5 ^b	0.67
DF3	26.8 ^b	29.4 ^a	23.9 ^c	23.1 ^c	29.5 ^a	0.67
DF4	28.3 ^b	34.1 ^a	23.3 ^c	22.8 ^c	29.2 ^b	0.67

^{a-c}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

Chemical Analyses

Samples were dried at 55°C for 24 h and ground in a Wiley mill (Arthur H. Thomas, Philadelphia, PA) to pass a 1-mm screen. Each sample was analyzed for CP (AOAC, 1990) and NDF and ADF (Goering and Van Soest, 1970).

Statistical Analyses

Geometric mean particle size, CP, NDF, and ADF were analyzed in a model that included the fixed effects of month, dairy farm (DF), and mixer or feed bunk location and pairwise interactions between these effects. The general linear models procedure of SAS (SAS Institute, 2001) was used and comparisons for significant ($P < 0.05$) variables were made using the PDIF option. Tabulated percentages of sample recovered on various sieves were also converted to lognormal distributions for graphical presentation.

RESULTS AND DISCUSSION

Nutrient Composition of TMR

The NDF contents of TMR are listed in Table 2. Differences in composition within DF but across months are related to changes in TMR formulations over time (Table 1). For example, DF1 fed TMR with more con-

Table 5. Particle size distribution of TMR¹ for different dairy farms

Sieve fraction, % retained in sieve	Dairy farm				SD
	DF1	DF2	DF3	DF4	
>19 mm	16.0 ^b	13.9 ^c	19.4 ^a	16.0 ^b	0.42
19 to 8 mm	36.1 ^b	37.6 ^a	34.2 ^c	33.0 ^d	0.42
8 to 1.18 mm	35.2 ^b	34.7 ^{bc}	33.6 ^c	38.0 ^a	0.42
<1.18 mm	12.7	13.8	12.8	13.0	0.42

^{a-d}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

Table 6. Particle size distribution of TMR¹ during 5 mo of the year

Sieve fraction, % retained in sieve	Month					SD
	April	May	July	August	October	
>19 mm	13.1 ^b	17.8 ^a	16.9 ^a	16.9 ^a	16.9 ^a	0.47
19 to 8 mm	36.7 ^a	35.9 ^{ab}	36.0 ^{ab}	35.1 ^b	32.5 ^c	0.47
8 to 1.18 mm	34.4 ^{bc}	33.7 ^c	35.7 ^b	35.2 ^b	37.9 ^a	0.47
<1.18 mm	15.8 ^a	12.6 ^b	11.4 ^c	12.8 ^b	12.7 ^b	0.47

^{a-c}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

concentrate in April and had its lowest content of NDF. In May, fresh alfalfa was incorporated into the TMR and concentrate was reduced, maximizing NDF content.

In general, NDF content of all TMR exceeded minimum recommendations for lactating dairy cows (NRC, 2001). These guidelines also pointed out that rations higher than 44% NDF may affect intake and digestibility of nutrients. In alfalfa-based diets it has been observed that chewing time is increased from 26 to 34% with an increase in NDF content (Beauchemin and Buchanan-Smith, 1989). The same effect was observed in barley-based diets (Beauchemin et al., 1994) and in

Table 7. Particle size distribution of TMR¹ sampled from various locations

Sieve fraction, % retained in sieve	Feed mixer	Feed bunk			SD
		Top	Middle	Bottom	
>19 mm	15.6 ^b	15.1 ^b	15.9 ^b	18.6 ^a	0.42
19 to 8 mm	35.5 ^a	35.8 ^a	35.7 ^a	33.9 ^b	0.42
8 to 1.18 mm	36.0 ^a	35.9 ^a	35.3 ^{ab}	34.3 ^b	0.42
<1.18 mm	12.9	13.2	13.1	13.2	0.42

^{a,b}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

corn silage-based diets (Oba and Allen, 2000). These results indicate that NDF stimulates chewing activity; however, concentrations higher than required may affect milk yield. It is possible that relatively high NDF contents of TMR in the present study limited performance.

Crude protein contents of the TMR are shown in Table 3. Although CP differed within DF over time, values were within the recommended range (17–19%) for high-yielding dairy cows (NRC, 2001). Others have reported similar results (Woodford et al., 1986; West

Figure 1. Particle size distributions of TMR from dairy farms 1 (♦), 2 (■), 3 (▲), and 4 (○). Connected points denote the range of observed data, whereas unconnected points were estimated assuming that the observed data conformed to a lognormal distribution. The probability density function (pdf) describes the distribution of particle size on a logarithmic scale.

Table 8. Particle size distribution of TMR on as-fed and DM basis

Sieve fraction, % retained in sieve	Wet ¹	Dry	SD
>19 mm	17.4 ^a	15.2 ^b	0.3
19 to 8 mm	37.3 ^a	33.2 ^b	0.3
8 to 1.18 mm	35.6	35.1	0.3
<1.18 mm	9.7 ^b	16.5 ^a	0.3

^{a,b}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

et al., 1999; Krause et al., 2002; Reynal and Broderick, 2003).

The ADF contents of TMR are given in Table 4. In general, the values of ADF were above of the minimum recommended for high-yielding dairy cows, but only on DF2 during August did the ADF value approach the minimum recommended (NRC, 2001). Bal et al. (2000) reported ADF contents of 24% and Woodford et al. (1986) reported ADF contents of 32 to 33% in corn silage-based diets.

Particle Size Distribution on the Dairy Farms

Particle size distribution of TMR on the 4 DF is shown in Table 5 and Figure 1. Particle retention on the 19-mm sieve was higher on DF3 and the lowest on DF2 (19.4 and 13.9%, respectively). These values were higher than the optimum recommended for this sieve, which is between 6 and 10% (Fisher et al., 1993; Lammers et al., 1996a). For the 8-mm sieve, all dairies differed. The lowest was DF4 and the highest was DF2 (33 and 37.6% of retained particles, respectively). The increase on the 19-mm sieve reduced retention on the 8-mm sieve. Values were within the range described by the TMR guides, where the percentage of retention for the 8-mm sieve is recommended to be from 30 to 50% (Lammers et al., 1996a). The percentage of retained material on the 1.18-mm sieve differed between DF; the highest value was for DF4 and the lowest was for DF3 (38 and 33.6% of retained particles, respectively). Despite differences between dairies for this sieve, values were within the 30 to 50% range recommended by TMR guides (Lammers et al., 1996a). All dairy farms

Figure 2. Particle size distributions of TMR in April (◆), May (■), July (▲), August (○), and October (●). Connected points denote the range of observed data, whereas unconnected points were estimated assuming that the observed data conformed to a lognormal distribution. The probability density function (pdf) describes the distribution of particle size on a logarithmic scale.

Table 9. Mean particle size (mm) of TMR¹ across 5 mo of the year

Dairy farm	Month					SD
	April	May	July	August	October	
DF1	5.7 ^c	7.1 ^a	6.8 ^{ab}	7.2 ^a	6.5 ^b	0.15
DF2	6.7 ^a	6.2 ^b	5.6 ^c	6.3 ^b	6.3 ^b	0.15
DF3	6.0 ^c	7.0 ^b	8.2 ^a	6.8 ^b	7.0 ^b	0.15
DF4	5.4 ^c	7.1 ^a	7.0 ^a	6.3 ^b	6.2 ^b	0.15

^{a-c}Means in the same row with different superscripts differ ($P < 0.05$).

¹Diets included water added during mixing.

had similar percentages of sample on the bottom pan, again within the 0 to 20% recommended by TMR guides (Lammers et al., 1996a).

Rippel et al. (1997) reported a distribution of particle size on sieves of >19, 19 to 8, and 8 to 1.18 mm of 18.4, 42.7, and 38.7%, respectively, for rations with silages and 22.2, 31.8, and 45.9%, respectively, for rations with hays. Lammers et al. (1996b) found particle size distributions of 6.1, 35.5, and 58.4%, respectively, whereas Heinrichs et al. (1999) reported distributions of 7.0, 35.0, and 58.0%, respectively, in dairy diets. These results differ from the present study (16.3, 35.2, and 35.4%, respectively) and may be related to forage:concentrate ratio. Forage in the present study

ranged from 49 to 62% of TMR and consisted of alfalfa hay plus corn silage in different proportions.

The results of Mertens (1997) and Yang and Beauchemin (2007) indicate that diets in the present study apparently provided adequate effective fiber for healthy ruminal function. Data of Righi et al. (2007) and Zebeli et al. (2008) suggest that forage:concentrate in the present study could be reduced somewhat, reducing the fraction >19 mm and increasing the fraction <1.18 mm, thereby improving digestion and milk yield.

Small particles were similarly distributed across farms (Figure 1); however, DF3 had a smaller proportion of medium particles and a higher proportion of large particles. This suggests that DF3 may benefit from additional concentrate in the TMR.

Particle Size Distributions Across Months

Particle size distributions differed with month of sampling (Table 6; Figure 2). Less material was retained on the 19-mm sieve in April (13.1%) than in May, July, and August (17.8, 16.9, and 16.9%, respectively). This could be explained by the shift of usage of alfalfa for corn silage. Results for April agreed with recommendations in the TMR guides.

Figure 3. Particle size distributions of TMR sampled from the mixer wagon (◆), the top of the feed bunk (■), the middle of the feed bunk (▲), or the bottom of the feed bunk (○). Connected points denote the range of observed data, whereas unconnected points were estimated assuming that the observed data conformed to a lognormal distribution. The probability density function (pdf) describes the distribution of particle size on a logarithmic scale.

Figure 4. Particle size distributions of TMR on an as-fed (♦) or DM basis (■). Connected points denote the range of observed data, whereas unconnected points were estimated assuming that the observed data conformed to a lognormal distribution. The probability density function (pdf) describes the distribution of particle size on a logarithmic scale.

Material between 8 and 1.18 mm was lowest in October (32.5%) and May (33.7%) but similar for April, July, and August (34.4, 35.7, and 35.2%, respectively). Particles <1.18 mm were highest in April (15.8%) and lowest in July (11.4%); May, August, and October were similar. In general (Figure 2), the lognormal distribution showed that April had higher proportions of small and medium particles and a lower proportion of large particles. Variation between small and medium particle distribution was small in other months, and the distribution of large particles was unchanged. These effects may have resulted from variation in TMR composition over time (Table 1).

Particle Size Distributions Within the Feed Bunk

Table 7 and Figure 3 describe the effect of sampling location with the feed bunk on particle size distribu-

tions. Samples obtained from the bottom of the feed bunk had more material >19 mm and less between 19 and 8 mm than those taken from other locations. Bottom samples also had less material between 8 and 1.18 mm than those taken from the top of the feed bunk or the mixer wagon.

Distributions of 19 to 8, 8 to 1.18, and <1.18 mm agreed with recommendations for TMR (30–50, 30–50, and <20%, respectively; Lammers et al., 1996a). More material was >19.0 mm (15–19%) than recommended (6–10%; Lammers et al., 1996a). Particle size distributions of samples from within the feed bunk were similar to those taken from the mixer wagon, which indicated that the TMR were properly mixed; however, it is unclear why the fraction of particles >19.0 mm was larger in samples from the bottom of the feed bunk (Figure

Table 10. Mean particle size (mm) of TMR on as-fed and DM basis

Dairy farm	Wet ¹	Dry	SD
DF1	7.2 ^a	6.2 ^b	0.1
DF2	6.8 ^a	5.6 ^b	0.1
DF3	7.8 ^a	6.2 ^b	0.1
DF4	6.8 ^a	6.0 ^b	0.1

^{a,b}Means in the same row with different superscripts differ (*P* < 0.05).
¹Diets included water added during mixing.

Table 11. Mean particle size (mm) of TMR on as-fed and DM basis through 5 mo of the year

Month	Wet ¹	Dry	SD
April	6.8 ^a	5.0 ^b	0.1
May	7.6 ^a	6.1 ^b	0.1
July	7.1 ^a	6.7 ^b	0.1
August	7.2 ^a	6.1 ^b	0.1
October	7.1 ^a	6.0 ^b	0.1

^{a,b}Means in the same row with different superscripts differ (*P* < 0.05).
¹Diets included water added during mixing.

3). Large particles are expected to rise to the top as samples settle (Rosato et al., 1987).

Particle Size Distributions and Water Addition

The influence of water addition on particle distributions of TMR is shown in Table 8 and Figure 4. As-fed samples had more material >19 mm and between 19 and 8 mm than did dried samples. Dried samples had more material <1.18 mm than did as-fed samples. These results may be attributable to the adherence of smaller particles on bigger particles with water addition, reducing material passing the smallest sieve. This is of practical importance because dust is reduced in TMR by water addition. Other authors have reported reduced sorting and an increment in NDF intake and milk fat percentage when water was added to dry diets (Leonardi et al., 2005).

Mean Particle Size of TMR Across Months

Mean particle sizes across months are shown in Table 9. For DF1, DF3, and DF4, TMR fed in April had smaller mean particle sizes than those fed in other months; however, those fed in April were larger than other months for DF2. All were large enough to support normal rumination, rumen function, and milk composition in dairy cows fed alfalfa hay (Woodford and Murphy, 1985; Woodford et al., 1986; Shaver et al., 1988).

Mean Particle Size and Water Addition

The effect of water addition on the geometrical mean of particle size of TMR in dairy farms is shown in Table 10. All dairy farms had higher mean particle sizes in as-fed than in dried TMR samples. The same was found for TMR across months (Table 11). Although mean particle sizes were higher in wet than in dry rations, all cases were acceptable (>5 mm) to maintain ruminal pH, ruminal activity, and fat milk (Woodford and Murphy, 1985; Woodford et al., 1986; Shaver et al., 1988).

CONCLUSIONS

Differences in particle size distributions throughout the year were related to changes in TMR composition. The TMR were properly mixed, but a higher percentage of particles >19 mm were present in samples from the bottom of the feed bunk than from other locations. Water addition during mixing reduced the percentage of smaller particles (<1.18 mm) in rations. Particle size and nutrient composition of TMR indicated that all were appropriate for normal rumen function and milk production.

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