Packing Bunkers and Piles to Maximize Forage Preservation

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Abstract. Forage is a valuable commodity stored on dairy farms. Bunker and pile silos have increased in use due to increasing herd size. Losses in feed value in bunker and pile silos are frequently higher than they should be because producers are not packing them sufficiently to exclude oxygen during the storage and feed out periods. The objective of this paper was to consider the recommendation of a minimum packing density of 240 kg dry matter/m^3 compared to a minimum bulk density recommendation to keep porosity low. Our conclusions are that producers should try to achieve a minimum bulk density of 700 kg as fed/m^3 while harvesting forage in the recommended range of 30-40% dry matter so as to limit porosity to a maximum of 0.4. This should result in lower losses of forage dry matter (DM) over a range of DM contents than when following the recommendation of a minimum packing density of 240 kg DM/m^3.

Keywords. Silage, Bunker Silo, Silage Piles, Density, Porosity, Dry Matter Loss, Feed Loss, Aerobic Decomposition.

Introduction

Forage is a valuable commodity stored on dairy farms. When stored in bunker and pile silos, dry matter (DM) losses can be in the range of 12-16% when good management is used in packing, covering and removing the feed from storage. A herd of 1000 cows consuming 11.3 kg DM/cow/day (25 lbs DM/cow/day) eats 4140 t/yr (4563 T/yr). If losses are 15% and silage is worth $88/t DM, the loss is $64,400. If losses increase by 10% due to inadequate oxygen exclusion, the additional value of feed loss becomes $42,900. Reducing this loss in feed value can help to defray the additional cost of improved management. The differences in losses due to silo management largely are a result of changes in the amount of aerobic microbial activity also known as aerobic deterioration.

<u>Aerobic Deterioration of Silage</u>

Aerobic deterioration of forage and silage occurs when the following conditions are met:

- Presence of oxygen
- Presence of sufficient numbers of aerobic organisms (yeasts, molds, bacteria)
- Presence of available substrates (sugars, starches, organic acids)
- Temperature above 4°C (40°F)
- Dry matter content less than 0.80 g/g (80%)

The rate of aerobic deterioration increases with increasing numbers of aerobic organisms, oxygen content, temperature, pH, available substrate and moisture content.

Forage preservation by ensiling is accomplished while avoiding the conditions conducive to aerobic deterioration. Practices to harvest at optimum moisture, exclude oxygen and lower pH are used to maximize the preservation of forage. These practices include harvesting at the stage of maturity that yields high sugar content and optimal moisture content, filling storages quickly, the use of oxygen limiting containers (silos), packing forage to high density, and addition of microbial inoculants. Practices to limit oxygen exposure during the feed out phase include: a large face removal rate (m/d, ft/d), minimizing disturbance of the feed out face and removing only the amount of feed needed for the current feeding.

Aerobic deterioration of forage releases carbon dioxide, water and heat. Of these, heat helps to accelerate the deterioration process. If the heat is limited from exiting the silage mass, temperature of the forage mass rises. Within limits (up to ~55°C or 131°F), aerobic microbial activity increases geometrically with temperature, approximately doubling for each 10°C (18°F) increase in temperature.

Discussion

Optimum Dry Matter Content for Ensiling

The optimum DM content for ensiling in a bunker or pile is not one set number for all situations. Typical recommendations are 30 to 40% for bunkers and piles. However, this range is a compromise between competing factors, and there are circumstances where forage can be in this range and still have poor preservation.

The competing factors are silage effluent, clostridial fermentation, aerobic deterioration and crop quality. The low DM limit is set generally by effluent losses and/or clostridial fermentation. When the density is sufficiently high so pores are filled with plant juices, seepage occurs. That effluent results in loss of feed value because it is high in dissolved nutrients and is potentially an environmental problem if not collected and properly disposed.

To avoid effluent, one generally needs to ensile above 30% DM or at less than 70% moisture. Effluent losses increase quadratically with increasing moisture content; for example (Bastiman and Altman, 1985):

$$Q = 4787 - 133.8\ m + 0.936\ m^2 \tag{1}$$

where Q = effluent production (l/t as fed)

m = moisture content (% as fed) for $m \geq 71.5\%$.

Clostridia are bacteria that produce butyric acid and amines in silage, reducing DM recovery from the silo and the palatability of silage and increasing the risk for ketosis in lactating dairy cattle. Growth of these bacteria can be avoided by achieving a sufficiently low pH from the normal lactic acid bacterial fermentation. That critical pH is affected by the crop and crop DM content (Fig. 1). Because corn silage routinely achieves a pH below 4.0, butyric acid is rarely found in corn silage. Grass and alfalfa silages are more susceptible to clostridial activity. With these crops, clostridial fermentation is rare for DM contents above 30% when harvesting under good conditions. However, cool, cloudy weather at harvest or rainfall during wilting can reduce sugar contents of forage crops and subsequently increase silage pH. Consequently recommendations within Wisconsin for ensiling alfalfa indicate a minimum DM content of 35% to avoid clostridial fermentation in bunkers or piles (Bolton and Holmes, 2006).

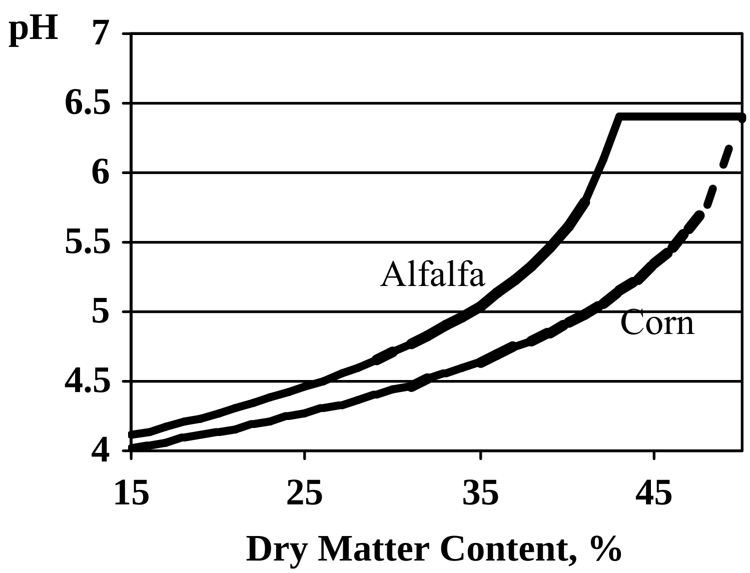

Figure 1. Critical pH below which *Clostridium tyrobutyricum* will not grow based on Leibensperger and Pitt (1987).

The high end of the recommended DM range for ensiling in a bunker or pile is set primarily by susceptibility to aerobic spoilage losses. A drier crop for a given packing procedure will be more porous and thus allow greater access of oxygen to the silage prior to feeding, increasing aerobic spoilage losses. The typical 10-point DM range between the minimum recommended moisture content and the maximum to avoid effluent or clostridial fermentation has been set for the most part arbitrarily as a good goal, and we will show below how porosity changes with moisture content. With corn silage, the 10-point range is also important for feed quality. Corn silage is cut and ensiled directly, generally as starch is still accumulating in the grain. The nutritive value of corn silage to lactating dairy cows increases with maturity up to approximately half milkline (Allen et al., 2003). Thereafter, corn silage quality declines. Dry matter content and milkline are correlated so that as the plant DM content increases above 40%, starch fill has advanced typically beyond half milkline and the corn will be harvested with poorer nutritive value.

Distribution of Dry Matter Losses in Bunkers

Assuming you ensile the crop dry enough to avoid effluent, losses fall into two principal categories: fermentation and respiration with each having subcategories.

Fermentation loss is primarily carbon dioxide gas produced anaerobically by lactic acid bacteria and other microorganisms as they utilize sugars and other substrates. Fermentation loss by lactic acid bacteria is typically between 1-4% and is usually considered unavoidable (McDonald et al, 1991). However, the use of silage inoculants containing homofermentative lactic acid bacteria can minimize these losses. Such losses will be relatively uniform throughout the silo. Fermentation losses by other microorganisms such as yeasts and clostridia are likely to be evenly distributed assuming the DM content of the crop is uniform. With clostridia in particular, activity and thus losses may be limited to wet layers (DM < 0.30 to 0.35 g/g) in a bunker or in layers immediately below spoiled silage.

Respiration losses come from two sources, plant and microbial. Plant respiration is active during the filling of the silo until the crop has become anaerobic when the silo is sealed. Typically with good management, this causes a DM loss of 1-2%. It should be relatively uniformly distributed throughout the silo. However, higher losses will occur in bands in a bunker or pile silo where filling has stopped overnight or at the top surface if silo covering is delayed. The 1-2% plant respiration loss plus the 1-4% fermentation losses by lactic acid bacteria represent the unavoidable losses (2-6%) from ensiling.

Most other losses come from microbial respiration - the activity of spoilage microorganisms utilizing oxygen that infiltrates the silo during storage or emptying and producing carbon dioxide. These losses, especially respiration during storage when the silo should be sealed, can be localized. Visibly moldy silage is evidence of prolonged exposure of silage to oxygen. The most common moldy areas in a bunker silo are beneath the plastic cover and extending down the shoulders next to bunker walls. Some of this loss is due to oxygen diffusing through the plastic cover. However, good management makes it possible to have a bunker or pile silo with no visible mold, meaning the diffusion of oxygen through a well-secured plastic cover can be small. This suggests moldy areas are the result of 1) holes in the plastic or cracks in the walls, 2) rainfall running off the top into silage at the walls carrying oxygen into the silage and washing away the preserving organic acids, and/or 3) plastic covers that are not held tightly to the crop so wind turns the cover into a bellows drawing oxygen into the silo. During emptying, losses are higher at the top of the bunker or pile silo where porosity is highest (i.e., density is lowest) and thus oxygen penetrates the fastest and deepest.

Average DM losses in bunkers or piles are expected to be higher than losses in tower silos, bags or wrapped bales (Muck and Holmes, 2006a). This is due primarily to a combination of low feed out rates, high porosities and plastic covers that frequently are not sealed adequately. Recently, we compared a bunker, bag and oxygen-limiting tower silo where all of second cutting alfalfa at a research farm was harvested within 2 d and divided among the three storage types. The experiment was repeated twice, and the average DM losses when the silos were emptied the following spring and summer were 4, 11 and 17% for the tower, bag and bunker, respectively (Muck, 2007, unpublished data). While higher average losses may be typical of bunkers or piles, catastrophic losses are more likely in bags and wrapped bales, which have a much higher surface area of plastic to volume of silage. Damage to plastic can result in DM losses of up to 40% in bags (Muck and Holmes, 2006b), a level of loss that is unlikely in a well managed bunker or pile.

Porosity

Porosity is a measure of the voids between the solid particles of a material. Pore space can be filled with fluids including gas and/or water in silage. The "air filled" porosity allows gases to move within the material. For gases to move throughout the material, the pores must be continuous. Closed pores do not contribute to gas flow. Porosity can be measured with a pycnometer (Mohsenin, 1986), which works best for granular materials like grains and stones, etc. To measure porosity in silage with a pycnometer, one needs to compress the sample in a perforated container as described by Rees et al (1983). Porosity (fraction) can be calculated as:

$$\phi = 1 - (\rho / \rho \max) \tag{2}$$

where ρ = bulk density

$\rho\max =$ maximum bulk density when all voids are removed

Pitt (1986) reports the specific gravity of silage dry matter for a variety of sources ranges between 1.42-1.7 g/cm^3. Using a value of 1.5 g/cm^3, Pitt calculated:

$$\rho\max\,(\text{g/cm}^3) = 3/(3\text{-DM}) \tag{3}$$

where DM = dry matter content (decimal).

Richard et al (2004) give an equation for air filled porosity as:

$$\phi = 1 - \rho wb * \{[(1-DM)/\rho w] + [DM * OM/\rho om] + [DM*(1-OM)/\rho ash]\} \tag{4}$$

where $\rho wb =$ bulk density (g/cm^3)

$\rho w =$ density of water (1 g/cm^3)

$\rho om =$ density of organic matter (1.6 g/cm^3)

$\rho ash =$ density of ash (2.5 g/cm^3)

DM = dry matter content (decimal)

OM = organic matter content (decimal of DM)

At 95% organic matter content Richard's equation becomes:

$$\phi = 1 - \rho wb * \{[(1-DM)/1] + [DM * 0.95/1.6] + [DM * 0.05/2.5]\} \tag{5}$$

and graphs as Figure 2:

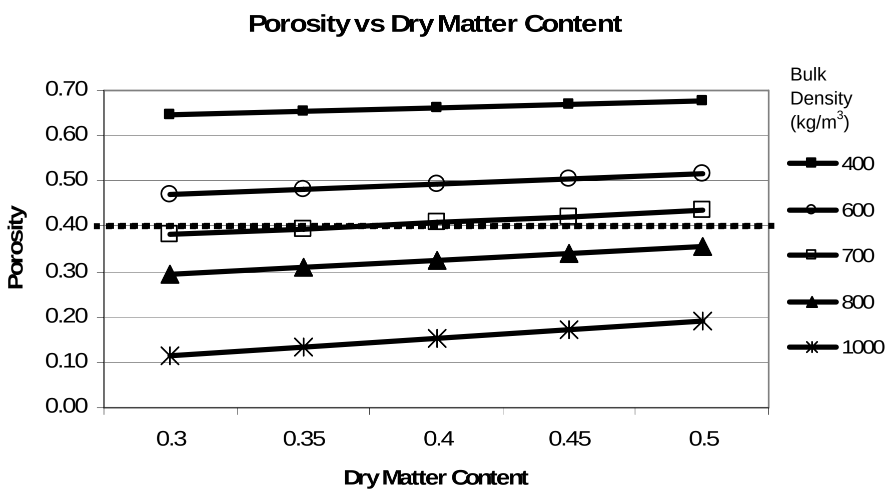

Figure 2. Graph of porosity (decimal) vs. dry matter content (decimal) for various bulk densities (Multiply bulk density (kg/m^3) by 0.06243 to obtain lbs/ft^3).

From Figure 2, porosity is most influenced by bulk density over the range of dry matter contents (0.3 – 0.4 g/g) recommended for ensiling in bunkers, bags and piles. Use of Pitt's equation (3 above) for maximum bulk density yields nearly the same results.

Thompson and Isaacs (1967), Ahn et al (2004), and Montross and McNeill (2005) show porosity is a linear function of bulk density over a range of materials with porosity decreasing with increasing bulk density similar to the theoretical analysis above. Bulk density increases and porosity decreases with particle size reduction for a given material at a given stress.

Mass Flow of Air in Silage

Oxygen can enter silage by diffusion and by volumetric flow. Volumetric flow occurs when the air surrounding a silo moves through the pores of the silage due to forces of air pressure differential. This pressure differential can be caused by wind, thermal buoyancy and difference in gas density. Ruxton and Gibson (1994) support the argument of Williams, Hoxey and Lowe (1997) that CO_2 being heavier than air will settle through silage and exit at the base of the feed out face of a bunker silo. The gas is replaced by air drawn into the feed out face near the top (Figure 3). The higher porosity of lower density silage at the top of the feed out face allows rapid movement of air into this zone. This air supports microbial activity that produces more CO_2 and heat. The heat increases temperature, which causes thermal buoyancy that causes gases in the silage to rise and exit the top of the feed out face. This exiting gas allows air to be drawn into the feed out face carrying oxygen to the zone of microbial activity (Figure 3).

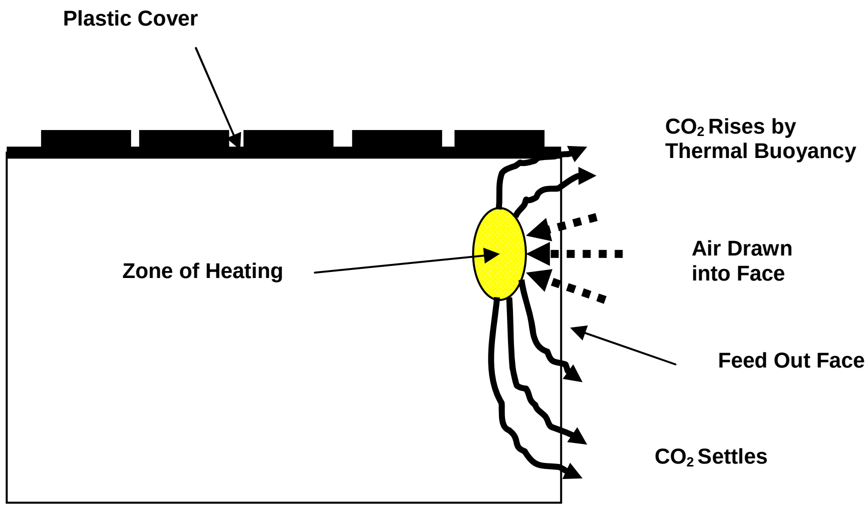

Figure 3. Longitudinal cross section of bunker silo showing volume flow of air.

According to Williams, Hoxey and Lowe (1997), the pressure difference causing CO_2 to settle is given by:

$$\Delta p = (\rho s - \rho a)gh \tag{6}$$

where ρs = density of silo gas
ρa = density of air
g = gravitational constant
h = height of the silo

They found the pressure difference is quite small, being 6.6 Pa for a 1 m tall silo containing 100% CO_2 at STP. The authors proceeded to solve for gas flow in porous media using Darcy's law to simulate air movement into the feed out face and CO_2 exit from the base. They also presented data on measured levels of CO_2, O_2 and temperature rise. One of their conclusions states "The hypothesis that gas movement in bunker silage is by permeation, as defined by Darcy's law, is partly confirmed by the data presented here."

Diffusion of Oxygen into Silage

Muck and Pitt (1994) simulated oxygen penetration into the face of a bunker silo using a diffusion model. The motive force for oxygen penetration is the difference in oxygen concentration in the air and the zero concentration in the anoxic zone of the silage. The diffusion of oxygen follows Fick's Law:

$$q = -D\ A\ \phi\tau(d\psi / dx) \tag{7}$$

where q = volumetric flow rate of oxygen
D = diffusion constant of oxygen through the surrounding gas
A = area through which the oxygen flows
ϕ = porosity of the silage
τ = tortuosity (distortion of the flow path frequently considered 2/3 (Bear, 1972))
$d\psi$ = difference in oxygen concentration
dx = difference in distance

McGechan (1990) describes tortuosity as the "… ratio of the path length through air to the path length through silage…". He mentions tortuosity values obtained by Rees et al (1983) are much lower than 2/3 and they decrease with increasing density and chop length.

The term $D\phi$ is sometimes referred to as the permeability (U). At the wall or plastic covered surface the effective permeability is:

$$U_{effective} = (1/U_{forage} + 1/U_{cover})^{-1} \quad (8)$$

where U_{forage} = permeability of forage
U_{cover} = permeability of cover or wall

Muck and Pitt (1994) assumed a uniform density and porosity over the height of the feed out face. They found "… the model predicted a more rapid progression of aerobic deterioration into the silage mass relative to the exposed face than actually occurred." When they reduced the porosity by 30%, the model predicted the temperature much more accurately. They theorized the 30% reduction in porosity accounts for closed pores that do not allow diffusion through them. Ruxton and Gibson (1994) performed a similar modeling procedure using a porosity that increased with depth above the floor of the bunker face. In their study, they predicted a higher oxygen flow into the top of the feed out face than the bottom with resultant higher temperature rise at the top of the face.

Reese et al (1963) related the diffusion constant in grass silage with the equation:

$$\ln D = -1.54 - 0.017 * CL - 0.00515 * \rho * (1-0.402 * DM) \quad (9)$$

where D = diffusion constant
CL = chop length of the forage (mm)
ρ = density (kg/m^3)
DM = dry matter content (decimal)

In equation 9, decreasing the chop length and increasing the dry matter content increase diffusion when density remains constant. Increasing density decreases diffusion when the other variables remain constant.

Porosity vs. DM and As Fed Density

As discussed previously, porosity is related to bulk density. Bulk density is a measure of material density including moisture. Equation 3 was used to generate table 1.

Table 1. Porosity and Dry Matter Density as a Function of Bulk Density and Dry Matter Content

Bulk Density (kg AF/m^3)			481	561	641	721	801	881
Dry Matter (decimal)	Max DM Density (kg DM/m^3)	Max Bulk Density (kg AF/m^3)	Porosity(%) (DM Density, kg/m^3)					
0.25	273	1091	55.9 (120)	48.6 (140)	41.3 (160)	33.9 (180)	26.6 (200)	19.2 (220)
0.30	333	1111	56.7 (144)	49.5 (168)	42.3 (192)	35.1 (216)	27.9 (240)	20.7 (264)
0.35	396	1132	57.5 (168)	50.5 (196)	43.4 (224)	36.3 (252)	29.2 (280)	22.2 (308)
0.40	462	1154	58.3 (192)	51.4 (224)	44.5 (256)	37.5 (288)	30.6 (320)	23.6 (352)
0.45	529	1176	59.1 (216)	52.3 (252)	45.5 (288)	38.7 (324)	31.9 (360)	25.1 (396)
0.50	600	1200	60.0 (240)	53.3 (280)	46.6 (320)	39.9 (360)	33.3 (401)	26.6 (441)

Multiply density (kg/m^3) by 0.06243 to obtain lbs/ft^3.

Holmes and Muck (2004) have recommended a minimum dry matter density of 240 kg DM/m^3 (15 lbs DM/ft^3) as a reasonably attainable density and to avoid excessive dry matter loss. From Table 1 it is apparent the porosity varies quite widely (~20 - 60%) for the combinations of dry matter content and bulk density that produce a dry matter density of 240 kg DM/m^3. That being the case, it may be better to recommend a maximum porosity in the range of 30-40%. However, because porosity is relatively constant for a given bulk density over a typical range of ensiling DM contents and because bulk density is more readily measured than porosity, it may be better to recommend a minimum bulk density. A minimum bulk density of 700 kg as fed (AF)/m^3 (43.7 lbs AF/ft^3) keeps porosity below 40% within the recommended range of DM.

Packing to achieve high density

Bulk density in silage is increased by self-compaction under its own weight, by applying pressure by tractor weight or bag rotor and by increasing moisture content. The classic system that applies pressure by self-compaction is the tower silo. The top 6 m of a tower silo has quite low density. A bunker or pile silo relying on self-compaction has low bulk density as well. Experience and research has shown silage made using self-compaction has much higher heating and dry matter loss than silage mechanically packed because mechanically packed silage has lower porosity.

Muck and Holmes (2000) found dry matter density in bunker silos is directly related to depth of silage, packing tractor weight, time spent packing and dry matter content and inversely related to forage layer depth before packing. An equation using these factors for predicting average dry matter density has been incorporated into spreadsheets (Holmes and Muck, 2006a, b) for both bunker and pile silos. The spreadsheet for bunker silos was modified to incorporate porosity using equation 5. Multiple scenarios were run using the spreadsheet assuming a layer thickness before packing of 0.15 m and an average fill depth of 4.3 m. The results are presented in figure 4. From figure 4, it is apparent porosity increases with harvest rate and increasing dry matter content. To keep porosity below 0.4, multiple heavy tractors and lower dry matter content is needed when harvest rate is high.

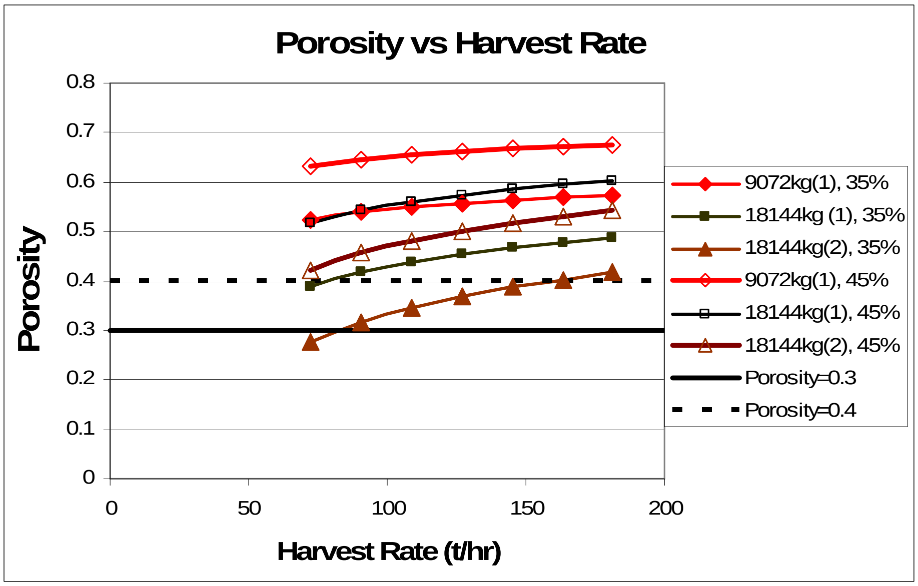

Figure 4. Porosity vs Harvest Rate for Different Tractor Weight (kg), (Number of Packing Tractors) and Dry Matter Content (%)

Holmes (2006) summarizes some of the research and field trials related to density achieved in tower and bunker/pile silos. Many field trials are finding:

Dry matter density is greater near the bottom of the silage than toward the top. (Muck and Holmes, 2000; Visser, 2005; Craig and Roth, 2005; D'Amours and Savoie, 2004; Oelberg et al, 2005) This may be due to self-compaction and more time spent packing the lower layers.

Dry matter density is lower next to the wall than in the center of the bunker/pile silo. (Visser, 2005; Craig and Roth, 2005; D'Amours and Savoie, 2004; Oelberg et al, 2005) This may be due to reduced packing time next to the wall and the lower depth on the sides of piles.

Average dry matter density is higher for hay than for corn silage. (Visser, 2005; Oelberg et al, 2005) This may be the result of faster harvest rate for whole plant corn than hay with resultant lower packing time for whole plant corn. Hay is often harvested at a higher dry matter than corn silage. Research has shown dry matter density to be directly related to dry matter content.

Increasing packing tractor weight, number of packing tractors and reducing layer thickness result in increased dry matter density. (Muck and Holmes, 2000; Visser, 2005; Craig and Roth, 2005; D'Amours and Savoie, 2004; Oelberg et al, 2005)

Feed out face

As discussed earlier, oxygen can enter the feed out face by both diffusion and volumetric air flow. Oxygen supports aerobic microbial activity, which can result in increased silage temperatures and rapid dry matter losses. High face removal rates reduce the time spoilage microorganisms have to grow and cause losses, and smooth feed out faces maintain the porosity at the feed out face similar to that achieved during filling, reducing oxygen movement into the silage.

The first step to achieving a high feed out face removal rate is to size the cross section area of the feed out face small enough when designing the bunker/silo pile. Holmes and Muck (2004) provide a procedure for sizing a bunker silo. Spreadsheets are available (Holmes, 1998 and Barnett, 2005) to simplify the sizing of bunkers and piles.

There are various means of making a smooth feed out face. A face cutter will provide the best surface. However, scraping silage from the feed out face with a downward or sideways slicing with a front end loader helps to maintain a smooth tight silage face. Creating a small cavity at the base of a feed out face and chipping small amounts of feed from above into the cavity can also be used with a front end loader. One of the worst practices is to ram the loader bucket into the feed out face and lift the bucket. This creates large fissures that allow oxygen to penetrate deeply behind the feed out face.

Bunker and pile silos should not be filled to a depth higher than the feed out equipment can reach. When silo faces are too tall, silage above the reach of the equipment is undermined. This overhanging material will avalanche posing a significant risk to those working or visiting in the fall zone as well as those removing plastic covers and spoiled feed from the top of the storage. Prior to avalanching, the overhanging silage pulls away from the rest of the silage mass. This opens fissures which allow oxygen to penetrate the silage from the top.

Conclusions

Aerobic deterioration of silage represents a significant loss to the dairy industry each year. These losses can be minimized by improved storage management. Following recommended management practices can go a long way toward achieving the goal of reduced feed value loss and improved profitability. Aerobic deterioration of silage is directly related to oxygen penetration into the silage by both volumetric movement of air and oxygen diffusion through pores within the silage. Pores can be minimized by harvesting at dry matter contents in the range of 0.3-0.4 and packing to a high bulk density. Silage in this range of dry matter should be packed to a minimum bulk density of 700 kg AF/m^3 (43.7 lbs AF/ft^3) to keep porosity below 0.4. Recommendations based on dry matter density alone do not adequately account for porosity.

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