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The Permeability and Porosity of Grass Silage as Affected by Dry Matter

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The permeability of silage is of great significance in aerobic deterioration. Relationships have been determined between permeability, porosity, dry matter content and density. Porosity is theoretically linearly related to density and this was confirmed experimentally. Permeability is theoretically directly related to porosity and hence to density for single phase fluids in solid matrices. The presence of moisture in silage, however, reduced permeability so that permeability (κ) was dependent on both density (ρ) and dry matter (D) according to the equation:

$$\kappa = 726 - 0{\cdot}368D - 0{\cdot}737\rho - 94{\cdot}0\,D/\rho,$$

where permeability is in μm^2, dry matter is in g/kg and ρ is in kg/m^3. The combination of this equation with a model that predicts silage density gradients allows vertical gradients of permeability to be predicted. In a 6 m diameter silo containing silage of initial density 400 kg/m^3 and dry matter content of 240 g/kg, the permeability would range between 280 μm^2 at the top to 2 μm^2 at the bottom. The significance of these results for the mathematical modelling of aerobic deterioration is discussed.

Notation

A	a parameter, Pa kg s^2
D	dry matter content, g/kg
k	horizontal to vertical pressure ratio, dimensionless
R	radius of silo, m
K	silage compressibility Pa^{-1}
g	gravitational acceleration, m/s^2
v	volume flow per unit area, m/s
P	pressure, Pa
x	distance, m
α	a coefficient, μm^2
β	a coefficient, μm^2 kg g^{-1}
γ	a coefficient, μm^2 m^3 kg^{-1}
θ	a coefficient, μm^2 kg m^{-3} g kg^{-1}
ϵ	dynamic viscosity of the gas, Pa s
κ	silage permeability, μm^2
μ	coefficient of friction between wall and silage, dimensionless
ρ	density of uncompressed silage, kg/m^3
ρ_0	density of silage at zero porosity, kg/m^3
σ	a coefficient
ϕ	silage porosity, dimensionless

1. Introduction

The aerobic deterioration of grass silage has great economic significance. UK agriculture is estimated to lose feed value of about £110 m annually by this process (Appendix 1). A second problem associated with aerobic deterioration is that *Listeria monocytogenes* can grow once the pH has risen above about 5·0, as occurs in the late stages of aerobic deterioration. *L. monocytogenes* is responsible for abortion, and possible death in ruminants, especially sheep, feeding on contaminated silage.[1]

Feed losses are caused by microbial populations, growing aerobically on substrates such as organic acids and water soluble carbohydrates. Yeasts, moulds and acetic acid bacteria play a major role in the initiation of aerobic deterioration by degrading simple, soluble substrates[2–4] although acetic acid bacteria do not appear to be found in grass silages.[5]

While micro-organisms cause deterioration, the process can be rate-limited by physical phenomena. Oxygen must penetrate silage to allow the micro-organisms to grow aerobically. Two mechanisms of oxygen penetration have been postulated; diffusion[6] which is governed by concentration gradients, and permeation[7] which is governed by pressure differences. Work at Silsoe Research Institute has shown that the major mechanism in bunker silos is probably permeation.[7]

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The initial pressure difference is generated by the difference in gas composition, and hence density, between the air outside and the gas within the silo. During ensiling, the air surrounding the grass elements is rapidly depleted of oxygen to form a mixture of about 79% N_2 and 21% CO_2. As fermentation proceeds, CO_2 is generated and gradually displaces most of the residual nitrogen to produce a CO_2 concentration approaching 100% (Ref. 8). During the following phase that normally lasts for several months, air may slowly leak into the silo as the denser silo gas escapes from the lower part. This phenomenon will occur in all but laboratory silos, since farm silos are not normally totally sealed. As air gradually passes into the silo, oxygen is consumed and converted to CO_2 by aerobic micro-organisms. By the time the silo is opened, in the autumn, the silo gas has reached equilibrium at about 79% N_2 and 21% CO_2 (Ref. 9).

Two major physical parameters that affect permeation rate are the permeability and porosity. This is shown in Darcy's law for permeation through porous media:

$$v = -(\phi \kappa / \epsilon)\, \partial P / \partial x \qquad (1)$$

where v is the volume flow per unit area (m/s), ϕ is the silage porosity, κ is the silage permeability (m^2), ϵ is the dynamic viscosity of the gas (Pa s), P is the pressure (Pa) and x is distance (m).

Gas viscosity is approximately constant within the range of temperatures (10 to 50°C) and gas compositions (79% N_2 and 21% O_2 to 79% N_2 and 21% CO_2) found in silage during feeding out, with a value of $18{\cdot}4 \times 10^{-6}$ Pa s varying by up to a maximum of 6%. This value would overestimate the extreme case of 100% CO_2 at 10°C by 8·8%. Rees *et al.*[10] established a linear relationship between porosity and density. Parsons and Hoxey[11] developed a method for measuring the permeability of silage under low pressure gradients, but it is a time-consuming measurement. It would be very helpful to be able to relate it to properties that are both easier to measure and are measured by other experimenters so that values of permeability in other experiments on aerobic deterioration may be inferred. This would cut the time needed for experiments and also allow permeability to be predicted in previously performed experiments or in farm silos.

It is necessary to know the value of permeability if predictions of aerobic deterioration are to be made using a mathematical model. A model of gas movement in silage using permeation as the mechanism has been constructed for a rectangular bunker silo.[7] This has been revised and is being extended[12] to include the model of microbial growth proposed by Courtin and Spoelstra.[13] In the model developed by Parsons,[7] permeability was assumed to be uniform throughout the silo. It is known from measurements[14] that density varies with depth and this has been included in other mathematical models.[15] This is essentially a consequence of self compaction such that the highest density is at the base of the silo. Rees and Neale[14] found a linear relationship between depth and density.

This paper describes measurements of permeability, porosity, density and dry matter in silages. Relationships have been produced between permeability, density and dry matter. Gradients of permeability in silos are predicted and their implications are discussed.

2. Methods and materials

2.1. *Silage making*

Two successive cuts of grass were made in the same field from a commercial seed mixture based on perennial ryegrass (UKF Ltd). The first cut was taken in May 1989 and the second in July 1989. Grass from each cut was collected immediately and, in addition, a portion of the July grass was wilted for 24 h. All the grass was collected by precision chop forage harvester, set at a nominal chop length of 26 mm. The chop lengths were determined by the method of Gale and O'Dogherty.[16]

Silages were made with a range of densities, from 250 to 850 kg/m^3. Nominally equal numbers of samples from the three treatments, over the range of densities were tested, but more results from the first cut samples were available and included in the present study since they were measured for other purposes beyond the scope of this paper. This was achieved largely at the time of ensiling, by pressing the grass into polyethylene film lined, galvanized steel containers, of 0·08 m^3 capacity, using a hydraulic press.[17] The neck of the polyethylene film was tightly tied with wire. No additives were used. The silages were stored in an unheated building until February 1990 when the silos were first opened and sampled with a 100 mm diameter corer.[17] Undisturbed sections of the 100 mm diameter cores, with length 137 mm, were placed in 100 mm diameter plastic cylindrical containers of overall length of 250 mm with the silage section held in place by perforated end caps and spacers.

The grass dry matter content was determined by oven drying at 105°C for 16 h. Silage dry matter content was determined by toluene distillation.[18] Density was determined by measuring the depth and diameter of the cores removed from each silo and the total mass of silage removed. Porosity was determined by the method of Rees *et al.*,[17] in which a sample of silage of known volume was placed in a cylinder attached by a valve to a pressurized reservoir of air. The valve was opened and from the final, stabilized air pressure the volume of connected voids in the silage and hence the porosity could be determined.

2.2. *Permeability measurements*

A technique to measure permeability under small pressure gradients has been developed at Silsoe Research Institute.[11] It involves raising the pressure of an air reservoir, upstream of the silage sample, by about 50 Pa, opening a valve downstream of the silage and measuring the exponential pressure decay curve. The curve is than analysed to determine permeability from Darcy's law. A high rate of decay indicates high permeability. This was used in the present study, but modified in the following way. Pressure changes were recorded by a pressure transducer (calibrated with reference to a standard maintained by the Dutch national calibration organisation–Nederlandse Kalibratie Organisatie) and a data logger, controlled by a microcomputer, which also pre-processed the data. A tap of 2 mm internal diameter, used to release pressurized air from the test chamber, was replaced with a solenoid valve of internal diameter 6 mm. The internal diameter of the tubing connected to the chamber was increased from 2 to 6 mm. These changes to the apparatus improved the consistency of measurements.

One aspect of the permeability measurement technique of Parsons and Hoxey[11] needed clarification. There might be a significant free air path between the silage sample and the container wall that could have artificially increased the measured permeability of samples. Lining the container with a layer of mineral grease could prevent this if it were a problem. This was investigated with the following procedure. Four cores were extracted from each of two silos of first cut grass with initial, nominal silage densities of 400 and 600 kg/m^3. Duplicate cores of each initial density were put into greased and ungreased containers while the spare cores were retained. Porosity, density and permeability were measured. Thin layers from the spare cores of each density were carefully removed and added to the silage in the other containers and the cores were compressed to 137 mm length hence increasing the density. Porosity, density and permeability were then determined again for the cores of increased density. This process was repeated several times until further layers could not be pressed into the containers.

2.3. *Theoretical relationships*

Porosity (ϕ) and density (ρ) are theoretically linked by the relationship:

$$\phi = 1 - \rho/\rho_0 \tag{2}$$

where ρ is density, and ρ_0 is the density at zero porosity.[19] Assuming that ρ_0 is constant (at a particular dry matter), a negative, linear relationship should be found between density and porosity.

Porosity and permeability (κ) have been linked by the equation:

$$\kappa = \phi/\sigma \tag{3}$$

where σ is a constant with dimensions of L^{-2} and is characteristic of the pore geometry.[19] It follows that, combining Eqn (2) and Eqn (3), the relationship between permeability and density would be:

$$\kappa = 1/\sigma - (\rho/\sigma\rho_0) \tag{4}$$

which is a linear function of ρ, if σ and ρ_0 are constant.

In fact, ρ_0 is not constant as it depends on the dry matter content and dry matter density of the silage and can be calculated from the following:

$$\rho_0 = \frac{\rho_d \rho_w}{(\rho_w d_f) + \rho_d(1 - d_f)} \tag{5}$$

where ρ_d is the density of grass dry matter (taken as 1420 kg/m^3 from McRandal and McNulty[20]), ρ_w is the density of water (1000 kg/m^3) and d_f is the fractional dry matter content. ρ_0 increases from a value of 1063 kg/m^3 for a dry matter content of 200 g/kg to 1194 kg/m^3 at 550 g/kg, so varying by 6% from a mean of 1129 kg/m^3. It is thus reasonable to regard ρ_0 as a constant.

Pitt[15] showed that the density gradient for self-compacted silage, is a function of several variables and can be described by the following equation which was derived from the Janssen formula for predicting loads exerted by grain in silos, but allowed for the compressibility of silage whereas grain is assumed to be incompressible.

$$\rho = \rho_u\left(1 + \left(\frac{1}{A-1}\right)\left(1 - e^{-(A-1)(Kgz\rho_u)}\right)\right) \tag{6}$$

where $A = 2\mu k/RKg\rho$, K is the silage compressibility (Pa^{-1}), R is the radius of silo (m), g is gravitational acceleration (m/s^2), k is the horizontal to vertical pressure ratio, z is depth in the silo (m), μ is the coefficient of friction between wall and silage, ρ is the density of silage at depth z (kg/m^3) and ρ_u is the density of uncompressed silage, i.e. at $z = 0$, (kg/m^3).

3. Results

3.1. *Grass properties*

The grass dry matter and chop lengths (Table 1) show that the dry matter was similar in the two fresh cut grasses, while the wilted grass contained about two-thirds of the moisture that was in the fresh cut grass. Chop lengths were similar throughout.

3.2. *Density and porosity*

The linear relationship suggested by Eqn (2) was confirmed (*Fig. 1*), with 84% variance accounted for. The data fitted the equation:

$$\phi = 0{\cdot}925 - 7{\cdot}43 \times 10^{-4}\,\rho \tag{7}$$

Table 1

Grass type	*Dry matter, g/kg*	*Median chop length, mm*	*Date ensiled*
First cut	253	31·2	18 May 1989
Unwilted second cut	238	28·1	20 July 1989
Wilted	545	27·1	21 July 1989

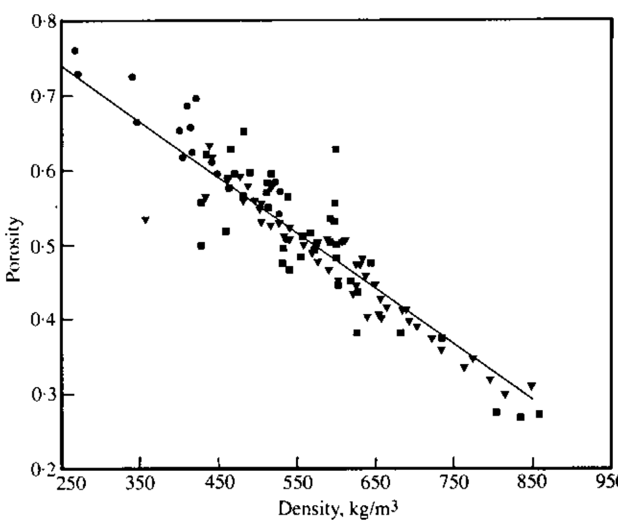

Fig. 1. Effect of density on porosity. First cut silage (■), second cut silage (▼) and wilted second cut silage (●)

with standard errors of $3{\cdot}73 \times 10^{-3}$ and $3{\cdot}01 \times 10^{-3}$ respectively, while fixing the constant at unity gave:

$$\phi = 1 - 8{\cdot}72 \times 10^{-4}\,\rho \tag{8}$$

with a standard error for the second coefficient $3{\cdot}78 \times 10^{-3}$, so agreeing closely with Rees *et al.*[10] who found:

$$\phi = 1 - 9{\cdot}19 \times 10^{-4}\,\rho \tag{9}$$

Using Eqn (9) with zero porosity gives value of maximum density of 1147 kg/m^3, which is within the range predicted by Eqn (5).

The relationship was slightly improved (with 86% variance accounted for) by calculating ρ_0 for each sample and fixing the constant at unity to give:

$$\phi = 1 - 0{\cdot}868\,\rho/\rho_0 \tag{10}$$

with a standard error for the second coefficient of $3{\cdot}30 \times 10^{-3}$. The smallness of the improvement suggests that given the other sources of variance in the system, it is reasonable to regard ρ_0 as a constant with respect to dry matter.

3.3 *Density and permeability*

3.3.1 *Greased and ungreased cylinders*

The measurements of first cut samples in greased and ungreased containers showed a strong linear relationship (accounting for 99·6% and 99·8% of variance for samples with initial densities of 400 and 600 kg/m^3 respectively) between density and permeability for each (*Fig. 2*). Analysis of the degree of parallelism between the greased and ungreased data for each sample showed no significant difference between them. Consequently, it was concluded that greasing was not necessary. The overall relationships were described by the following equations for 400 kg/m^3 initial density,

$$\kappa = -0{\cdot}782\,\rho + 646 \tag{11}$$

with standard errors of 0·467 and 3·84 respectively and for 600 kg/m^3 initial density,

$$\kappa = -0{\cdot}439\,\rho + 373 \tag{12}$$

with standard errors of 0·220 and 1·90 respectively. Permeability has the units μm^2, with density in kg/m^3.

4. Permeability and density

For most cores, the effect on permeability of increasing density was similar, but the slope and

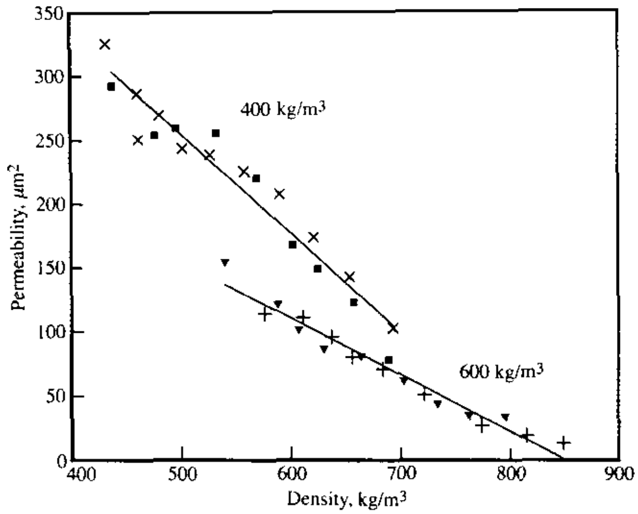

Fig. 2. Permeability and density with silages in greased and ungreased containers and with original densities of 400 and 600 kg/m³. The regression lines from Eqns (11) and (12) are shown. Key: 400 kg/m³ greased (■), 400 kg/m³ ungreased (×), 600 kg/m³ greased (▼) and 600 kg/m³ ungreased (+)

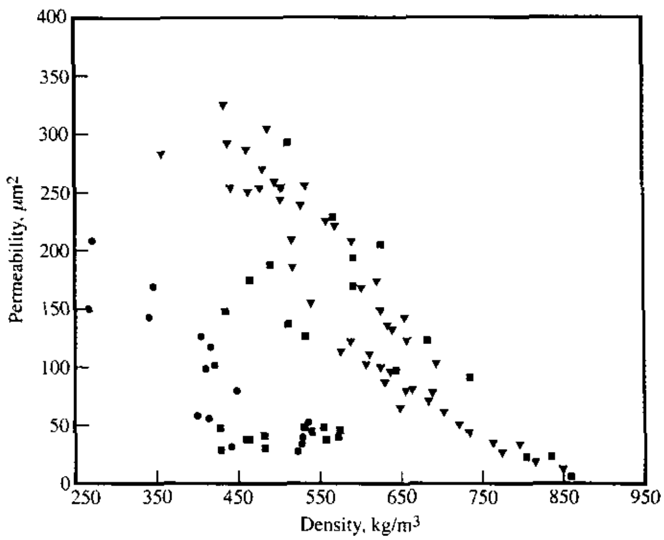

Fig. 3. Effect of density on permeability. First cut silage (■), second cut silage (▼) and wilted second cut silage (●)

intercept of the relationships varied considerably between treatments (*Fig. 3*). The differences could be associated with varying dry matter contents. The overall correlation was poor with dry matter accounting for only 23% of the variance.

While these results contrast with the relationship postulated in eqn (3), it should be noted that the constant σ, was for fluid flow in a solid matrix. The nature of silage is different as the matrix has a variable moisture content; some of the moisture is bound within the solid structure while some occupies interstitial spaces. It is reasonable to expect that, at increased moisture contents some airways may be blocked against air movement (especially with the low pressure gradients used to measure permeability). It was thus postulated that there would be a relationship between dry matter (D) and permeability (for a particular density) taking the general form:

$$\kappa = \alpha - \beta D \tag{13}$$

and given the linear relationship between permeability and density in Eqn (4), a composite relationship (including a term to allow for the interaction between density and dry matter) was expected taking the form:

$$\kappa = \alpha - \beta D - \gamma\rho - \theta D/\rho \tag{14}$$

This was tested using multiple linear regression and the following equation resulted:

$$\kappa = 723 - 0{\cdot}368\,D - 0{\cdot}737\,\rho - 94{\cdot}0\,D/\rho \tag{15}$$

where permeability is in μm², density in kg/m³ and D in g/kg. The standard errors of the coefficients (α, β, γ and θ) were 31·5, 0·085, 0·053 and 27·8 respectively. This equation accounted for 79% of the variance (*Fig. 4*). Treating ρ_0 as a variable, rather than a constant, had even less effect than with the porosity and density relationship and still accounted for 79% of variance. Negative permeabilities can be predicted with Eqn (15), in which case permeability should be regarded as being zero. There is not a simple limit to the values of density and dry matter that can be used with confidence, but generally outside the experimental range of dry matters (250 to

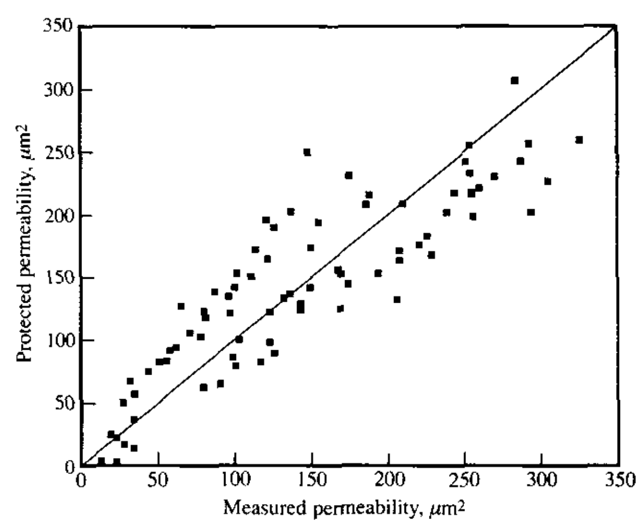

Fig. 4. Permeability predicted from density and dry matter used Eqn (15). The ideal line is also shown

550 g/kg) and densities (250 to 850 kg/m^3), predicted permeabilities should be treated with caution.

Including terms for porosity and chop length gave a negligible improvement in accounting for variance in the relationship between measured and predicted permeability. Little effect would be expected from chop length as all treatments had similar values, and porosity is closely correlated with density (*Fig. 1*).

4. Prediction of vertical permeability gradients

The Pitt[15] model [Eqn (6)] was developed for tower silos and has not been tested under conditions in the UK. Nonetheless, it gives a useful insight into how densities may vary in a bunker silo where the contents have not been artificially compressed.

Combining Eqn (6) with Eqn (15) provides a means of estimating gradients of permeability in silage (*Fig. 5*). The following parameter values were used: dry matter = 240 kg/m^3, $K = 5{\cdot}5 \times 10^{-3}\,\mathrm{Pa}^{-1}$, $R = 6$ m, $g = 9{\cdot}81$ m/s^2, $k = 0{\cdot}5$, $z_{max} = 4$ m and $\mu = 0{\cdot}4$. ρ_0 was set at values from 200 to 600 kg/m^3 at 100 kg/m^3 intervals. *Fig. 5* shows that both initial density and depth of silage have a major effect on permeability. Silage at the top of a silo will be more at risk of aerobic deterioration than that at the base, due to permeability alone.

The model proposed by Parsons[7] showed that, with uniform permeability, deterioration started at the top of the exposed face of a bunker silo. This resulted from the introduction of air at the top while denser silo gas leaked out from the base. Gas flow patterns will clearly be affected by vertical permeability gradients. The precise nature will need to be determined by further modelling, since opposing forces will be at work. On the one hand, it will be potentially easier for air to enter at the top, but if the permeability is very low in the lower regions of the silo, the denser gas will be impeded in leaving the silo and this will restrict air entering at the top. Furthermore, minimal permeability in the lower part of the silo will effectively move the base upwards, reducing the working height of the silo gas that produces the pressure difference, which is the driving force behind permeation.

5. Relationship between density, dry matter and density

Aerobic deterioration losses could be eliminated by making silage impermeable and thus preventing oxygen passing through the silage. This is impossible, however, in normal farm practice and silage will be appreciably permeable. Various biological factors may limit aerobic deterioration, such as a low concentration of spoilage organisms or high concentrations of inhibitory compounds, such as organic acids. Given some knowledge of these factors it may be possible to define a maximum value of permeability for a particular silage so that the risk of deterioration is acceptably low. At present, values cannot be defined, but if a range of 25 to 250 μm^2 is considered, values of the density that must be achieved for a known dry matter can be calculated from Eqn (15). These are shown in *Fig. 6*.

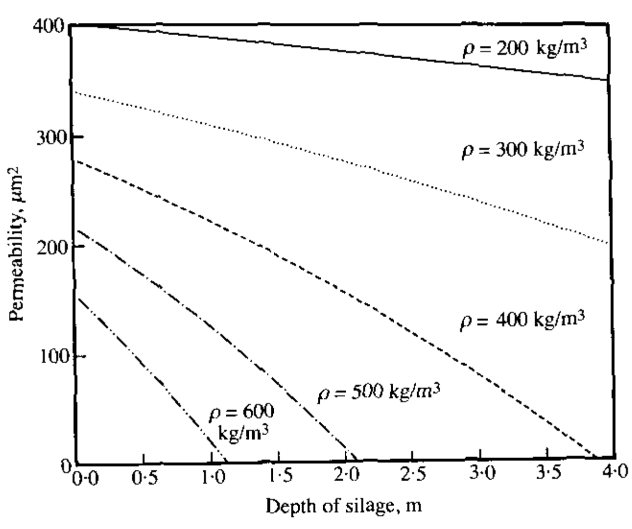

Fig. 5. Vertical permeability gradients predicted from Eqn (6) and Eqn (15) for silages with uncompacted densities of 200 to 600 kg/m^3

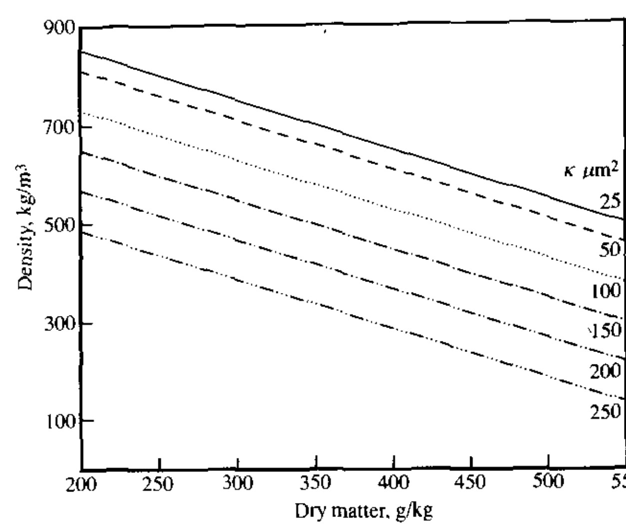

Fig. 6. Range of dry matter and densities that produce permeabilities of 25 to 250 μm^2, calculated from Eqn (15)

Fig. 6 shows some of the constraints that may be inferred from Eqn (15). It is evident that a uniform low permeability of 25 μm^2 will be difficult to achieve in practice, given the relatively high densities needed throughout the range of dry matter, although it may be possible at the bottom of a silo where density is greatest.

It appears from *Fig. 6* that pre-wilted grass will enable a target permeability to be reached more easily than for fresh cut grass as the desired density is reduced. This may not, in practice, however, be so easy to attain. Drier forages tend to be progressively more difficult to compress.[21,22] Daynard *et al.*[22] showed that increasing maize dry matter from 270 to 380 g/kg required the applied pressure to be doubled to achieve the same density. Drier forages also have lower densities, which reduces self compression. This clearly may make a target density unattainable and may partly explain the observation that high dry matter silages tend to be susceptible to aerobic deterioration.[23] An additional reason is that higher dry matter forages often have restricted fermentations and hence higher pH values, which renders them more susceptible to deterioration. The physical condition of high permeability is likely to be the cause because drier silages would otherwise be less biologically susceptible to aerobic deterioration since the low water activity reduces microbial growth rates.[13] A comprehensive predictive mathematical model of aerobic deterioration and silage compression is needed to test these relationships further.

6. Conclusion

Permeability is linearly related to both density and dry matter. Porosity is linearly related to density and the results were very similar to those found in an earlier study.

Vertical gradients of permeability with silage depth were predicted from the relationship shown in the present study and from a model of Pitt.[15] Such vertical gradients will modify the flow patterns suggested by the model of Parsons.[7]

The attainment of a desired minimum acceptable permeability may be limited by the compressibility of grass, especially when wilted. This may be why drier silages tend to be more prone to aerobic deterioration.

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References

1 **Fenlon, D. R.** Listeriosis. In Silage and Health, Stark B. A. and Wilkinson, J. M., Marlow Bottom, Chalcombe Publications, 1988, 7–18

2 **Muck, R. E.; Pitt, R. E.; Leibensperger, R. Y.** A model of aerobic fungal growth in silage. 1. Microbial characteristics. Grass and Forage Science 1991, **46:** 283–299

3 **Spoelstra, S. F.; Courtin, M. G.; Van Beers, J. A. C.** Acetic and bacteria can initiate aerobic deterioration of whole crop maize silage. Journal of Agricultural Science; Cambridge 1988, **111:** 127–132

4 **Middelhoven, W. J.; Van Baalen, A. H. M.** Development of the yeast flora of whole-crop maize during ensiling and during subsequent aerobiosis. Journal of the Science of food and Agriculture 1988, **42:** 199–207

5 **Duffus, C. M.; Sutherland, I. W.; Wilkinson, J. F.** The importance of acetic acid bacteria in the aerobic deterioration of grass silages in Scotland, and related studies. Report to the Agricultural and Food Research Council (Ref. AG15/528) AFRC, Swindon, 1992

6 **Pitt, R. E.** Dry matter losses due to oxygen infiltration in silos. Journal of Agricultural Engineering Research 1986, **35:** 193–206

7 **Parsons, D. J.** Modelling gas flows in a silage clamp after opening. Journal of Agricultural Engineering Research 1991, **50:** 209–218

8 **McGechan, M. B.; Williams, A. G.** A model of air infiltration losses during silage storage. Paper Presented at Ag Eng 90, Berlin, October 1990

9 **Hoxey, R. P.** Factors controlling the aerobic deterioration of silage. In: Engineering advances for agriculture and food. Cox, S. W. R. (ed), London, Butterworths, 1988, 139–140

10 **Rees, D. V. H.; Audsley, E.; Neale, M. A.** Some physical properties that affect the rate of diffusion into silage. Journal of Agricultural Science; Cambridge 1983, **100:** 601–605

11 **Parsons, D. J.; Hoxey, R. P.** A technique for measuring the permeability of silage at low pressure gradients. Journal of Agricultural Engineering Research 1988, **40:** 303–307

12 **Williams, A. G.; Critten, D. L.; Reynolds, A. P.** A model of the aerobic deterioration of silage. Proceedings of the 10th International Conference on Silage Research. Dublin City University, 6–8 September 1993, 120–121

13 **Courtin, M. G.; Spoelstra, S. F.** A simulation model of the microbiological and chemical changes accompanying the initial stage of aerobic deterioration of silage. Grass and Forage Science 1990, **45:** (2), 153–166

14 **Rees, D. V. H.; Neale, M. A.** An experiment to determine some of the changes that occur in silage during unloading from mini-tower silos. Divisional Note DN 1170, National Institute of Agricultural Engineering, Silsoe, 1983

15 **Pitt, R. E.** Mathematical prediction of density and temperature of ensiled forage. Transactions of the ASAE 1983, **26:** 1522–1527, 1532

16 **Gale, G. E.; O'Dogherty, M. J.** An apparatus for the assessment of the length distribution of chopped forage. Journal of Agricultural Engineering Research 1982, **27:** 35–43

[17] **Rees, D. V. H.; Audsley, E.; Neale, M. A.** Apparatus for obtaining an undisturbed core of silage and for measuring the porosity and gas diffusion of the sample. Journal of Agricultural Engineering Research 1983, **28:** 107–114

[18] **Collins, R. E.** Flow of fluid through porous materials. New York, Reinhold Publishing Corporation, 1961

[19] **Dewar, W. A.; McDonald, P.** Determination of dry matter in silage by distillation with toluene. Journal of the Science of Food and Agriculture 1961, **12:** 790–795

[20] **McRandal, D. J.; McNulty, P. B.** Mechanical and physical properties of grasses. Transactions of the ASAE 1980, **23:** 816–823

[21] **Wood, J. G. M.** The properties of ensiled crops and why we have to design for them. In: Proceedings of the International Silage Research Conference, National Silo Association, Cedar Falls, Iowa, 1971, 296–322

[22] **Daynard, T. B.; Arnold, R. L.; Bellman, H. E.** Density-pressure-seepage relationships of whole-plant corn (Zea mays L.) silage. Canadian Agricultural Engineering 1978, **20:** 45–52

[23] **McDonald, P.; Henderson, A. R.; Heron, S. J. E.** The Biochemistry of Silage. Second edition. Chalcombe Publications, Marlow, 1991, 162–163

[24] **Woolford, M. K.** The detrimental effects of air on silage. Journal of applied Microbiology 1990, **68:** 101–116

APPENDIX A

Estimation of value of UK silage loss

The annual UK silage production is about 55 Mt. If the average dry matter content is assumed to 20%, the total dry matter production is 11 Mt. With an estimated cost of production of dry matter at £84/t, the total value is £924 M. Woolford[24] found that dry matter losses caused by aerobic deterioration ranged between 5 and 25%. Assuming that the loss is 8%, the cash loss is £74 M, but the lost dry matter during aerobic deterioration is likely to be highly digestible. The lost dry matter could have a digestibility of up to 90% compared with an overall 60% for silage, thus the cash loss is proportionately greater and is effectively equivalent to a 12% dry matter loss with a cash cost to UK agriculture of £110 M annually.