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Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms

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Research on the incidence and effectiveness of natural crusting on slurry storage as a means of ammonia emission abatement was undertaken in studies at farm-scale, pilot-scale and on a small-scale. At the farm-scale, slurry crusting was found to be commonplace across a large proportion (ca 80%) of slurry storage facilities, despite the fact that regular store mixing and agitation was found to be carried out on 68% of farms. Observations provided information on the impact of a range of factors on the potential for crust formation. The most important factors were slurry solids content (crusting increasing with dry matter (DM) content), volume:surface area ratio of the storage (influencing nature of the crust and rate of formation), livestock diet (crusting more likely with grass silage), slurry management (agitation). Of particular importance, were weather conditions with evaporation increasing crusts and rainfall having the opposite effect.

From measurements at farm- and pilot-scale (i.e. excluding small-scale comparative studies), mean ammonia emissions were 1.07 and 3.42 $g\,m^{-2}\,d^{-1}$ NH_3-N, for crusted and non-crusted slurry stores, respectively. Where direct comparisons between crusted and non-crusted slurry were possible, a reduction in NH_3 emission of about 60% was typical during the measurement period. Although the range in emission measurements was large, the results reported here have confirmed the potential for significant abatement under practical farm conditions. Assuming that natural crusting is as effective in reducing emissions as these results suggest, an objective assessment of crust integrity needs to be developed to assist with effective implementation of mitigation policy. A type of 'crustometer' could be developed, at least partly based on the falling weight technique described and tested briefly within the field studies. The work has also identified potential for a modelling approach for the prediction of crust development and, hence, likely emission abatement efficiency.

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1. Introduction

There are international pressures to reduce ammonia emissions from agriculture, as transboundary transport and subsequent deposition can damage fragile ecosystems. Manure storage is known to represent a significant source of gaseous emissions from agriculture, including ammonia and methane. Misselbrook *et al.* (2006) estimated that manure storage was responsible for about 13% of total NH_3-N emissions in the UK, with cattle manure storage emissions alone, estimated at 22 kt^{-1} year and pig manure storage 3.8 kt^{-1} year. The exposed surface area of stored manure is thought to have a substantial impact on NH_3-N emissions (Sommer *et al.*, 1993); storage method, physical form of the stored manure and source of manure (livestock type) are also likely to affect emission rates. Slurry crusting affects the exposure of liquid manure surfaces and has been shown to be effective in reducing NH_3-N emissions from stored slurry. Sommer *et al.* (1993) found slurry crusts as effective as a number of other artificial covers, reducing emissions by as much as 80%.

Around 50% of dairy farms, in England and Wales, and a similar proportion of pig farms, handle manure as slurry (Nicholson & Brewer, 1997; Smith *et al.*, 2000, 2001). Thus, strategies that can reduce emissions from slurry storage systems may have a significant impact on total national gaseous emissions. Whilst a number of low-cost covers have been considered, these appear to be too expensive for farmers to recover the costs through the value of retained ammoniacal N (Williams, 1998). Because of the importance of viable NH_3-N mitigation measures, it is important that a further investigation and evaluation of the effectiveness of natural crusting be undertaken.

If crusting is effective in reducing emissions, guidance on what constitutes a satisfactory crust should be established and how crust formation can be encouraged; also on how the crust should be managed, bearing in mind that the store will need to be completely emptied, probably at least once a year. Crusts left for longer periods than this can reduce the capacity of the store, may become colonised by vegetation including small trees and may become very difficult to break up. The most effective form and thickness of crust remains to be identified, as well as the factors that will promote and accelerate crust formation. The latter may include slurry solids content, amount and type of bedding used, diet (especially the impact of grass silage or forage maize) and some aspects of store management, such as top- versus below-surface filling and also, frequency of filling. Slurry type and slurry solids content are known to affect flow properties and settling characteristics of slurries (Robertson, 1977). It is possible that there may be an optimum range in slurry dry matter (DM) content, for rapid and effective crusting. Advice in the recent past has tended to favour regular store mixing and the avoidance of crust formation (Grundey, 1980), including advice to "inspect the store regularly and mix or recirculate at the first sign of crust formation" (Anon, 1989). Work within the project was necessarily restricted to cattle slurry, in which surface crusting is commonplace, since crusts are rarely seen in pig slurry.

2. Materials and methods

2.1. *On-farm studies*

A questionnaire was used to collect information on slurry crusting, livestock and store management on a sample of 50 dairy farms chosen to be representative of some of the major dairying areas in England. Further visits were later undertaken to a sub-sample of farms where crusting of the store was commonly anticipated. A hydraulically operated inspection platform, with purpose-built safety cage (EPL, Aston, Birmingham), was hired to allow safe inspection, sampling and assessment of the surface crust on at least two occasions during the storage season [Fig. 1(a)].

A prototype tool for assessment of crust thickness was developed. The device consisted of a rigid plastic tube and nipple for attachment of an inflatable rubber sack (*aka* balloon). The rigid plastic tube was inserted through a pre-drilled hole in the crust and the rubber sack inflated below the crust, allowing the distance between the shoulders of the

Fig. 1 – Measurements and assessments on slurry stores: (a) inspection platform used on farm stores and (b) ammonia extraction cover on pilot-scale tank at Silsoe Research Institute.

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inflated part and the crust surface to be measured. A hand-held penetrometer (Farnell, Hatfield, Herts), modified by the use of a circular metal disc (diameter 57 mm) to replace the standard cone, was used to measure the penetration resistance of the crust (force-plate penetrometer). The maximum reading registered on the penetrometer was recorded to indicate the force required to penetrate the crust completely.

A second approach was developed, aimed at addressing the need for some form of objective assessment of when a crust can actually be described as a 'crust', rather than as a layer of surface scum. The latter can have the appearance of a thin crust but none of the benefits in terms of reducing emissions. Such a method might also provide information on the ease with which a crust might be broken up by agitation and recirculation of the slurry via surface jet or impeller. At one site, in a store containing a crust ranging in thickness between 47 and 100 cm, a weight of 2.24 kg, with surface area of 38.5 cm^2, was dropped vertically from heights varying incrementally by 0.5 m, from 0.5 to 3.0 m. Following impact with the crust surface, the depth of penetration was recorded.

On some visits, vented cover-boxes (from the Silsoe Research Institute, SRI) were used to measure ammonia emissions from the surface of the stores. Ammonia collected in diffusion samplers within both the hood inlet and outlet are measured simultaneously, with the difference between the two measurements representing the ammonia flux from the surface of the slurry, over the assessment period. Two cover-boxes were deployed simultaneously, thus allowing a comparison of emissions from disturbed and undisturbed crust. Samples of crust and slurry from the stores were analysed for dry matter (DM), pH, total N, organic carbon and total ammoniacal N (TAN).

2.2. *Pilot-scale studies*

The experiments at SRI were completed using a set of 10, circular steel storage tanks. These enabled detailed observations of slurry crusting and influencing factors (climatic impacts, formation, strength, thickness and resistance to liquid mixing). An adjustable working gantry allowed access to crusted slurries in the tanks with a wide variety of slurry depths to enable strength and depth measurements to be undertaken safely. Ammonia emissions were measured by headspace air extraction from beneath vented lids [Fig. 1(b)]. Ambient and exhaust air was sampled for ammonia, using aspirated acid bubblers, with sampling periods typically of a few hours.

Procedures to assess the impact of climate and other factors on crust formation included measurement of crust thickness, strength and slurry depth. Also, meteorological data were collected by automatic weather station located next to the slurry tanks, throughout the measurement period. These data were recorded as mean values determined at 10-min intervals, including relative humidity, solar radiation, air temperature, rainfall, wind speed and direction. The slurry temperatures in the tanks were also recorded in a similar way. The data were used subsequently to calculate accumulated rainfall and potential evaporation. The results of these weather-based calculations were then compared with records of crust formation in each of the tanks.

2.3. *Small-scale studies*

Circular water cisterns (Plastech, Bradford) were used as small-scale slurry stores. The tanks had a total capacity of approximately 680 l, with a height of 0.75 m and top diameter of 1.06 m. When filled with 500 l slurry, there was a freeboard of 0.12 m between the slurry surface and the top of the tank.

The circular lids supplied with the tanks were modified to form an NH_3 sampling array. A centrally located fan (0.16 m diameter) drew air across the slurry surface through six inlet holes (0.03 m diameter) cut at regular intervals around the perimeter of the lid. Acid-coated glass wool was placed across the inlet holes to remove any NH_3 from the inlet air. Emission rates were measured over a 2-h period, generally at weekly intervals. Fans were set to run at 2 m s^{-1} through the central duct, generating an air speed across the slurry surface of approximately 0.2 m s^{-1}. Observations of crust formation, thickness and extent were made on a weekly basis for the majority of experiments.

3. Results and discussion

3.1. *Crust development in farm stores*

A slurry crust was found in 39 (78%) of the 50 stores initially inspected. Though crust incidence appeared greater in above ground tanks than in other store types, and in the Midlands and North of England, this is likely to have been coincidental and the result of factors other than store design or climate. Similarly, whilst there appeared to be a trend towards crusting with a grass silage diet compared with maize, there is insufficient evidence for conclusions. Full data from all these and other components of the research are available in the final project report (Smith, 2003).

Whilst slurry composition might be expected to have a strong influence on the predisposition towards crust formation, comparison of the incidence of crusting with slurry solids content data did not provide strong evidence in support of this hypothesis [Fig. 2(a)]. These data suggest that there may be an optimum range of slurry solids content (typically 60–140 g l^{-1}) for crust formation. However, this sample of stores does not allow a controlled comparison and, moreover, the analyses of input slurry may differ significantly from that of the material in store. The results of the controlled experiments using small-scale tanks, as reported in detail by Misselbrook *et al.* (2005), showed slurry solids content to be an important factor in crust formation, with no crust development on slurry with a solids content of <10 g l^{-1}.

Slurry crust formation is encouraged by gasification, i.e. the release of gases, including CO_2 and CH_4 during anaerobic storage, a process in which the bubbles tend to coalesce around fibre particles, the fibre inevitably rising to the store surface. It follows that a deep store will provide greater opportunity for slurry fibre to be carried towards the surface by gas bubbles than a wide, shallow store. This hypothesis does appear consistent with the observed data [Fig. 2(b)], in which increasing the volume/surface area ratio (approximating to slurry depth) does seem to be associated with increasing incidence of crusting. The two instances

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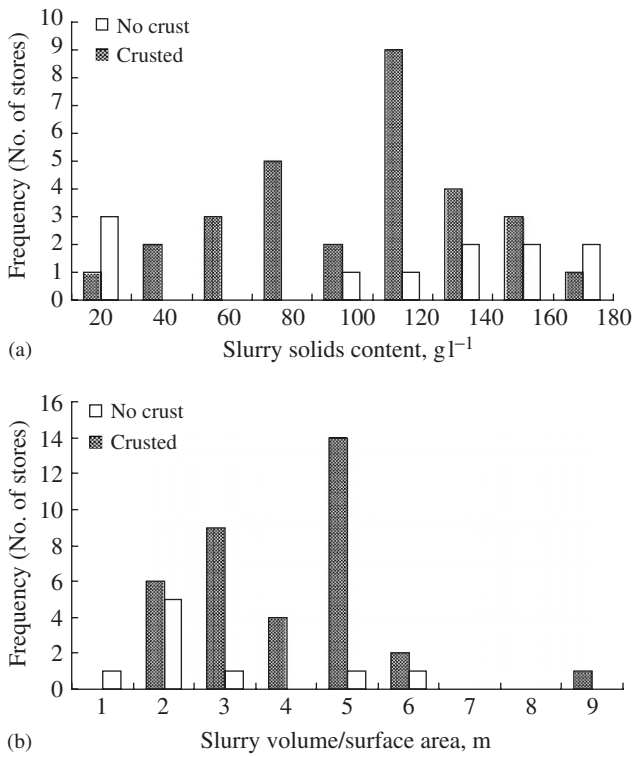

Fig. 2 – Incidence of crust formation during slurry storage and comparison with slurry analysis and store management factors (assessments based on initial site inspection); (a) slurry solids content and (b) slurry storage volume/surface area (m).

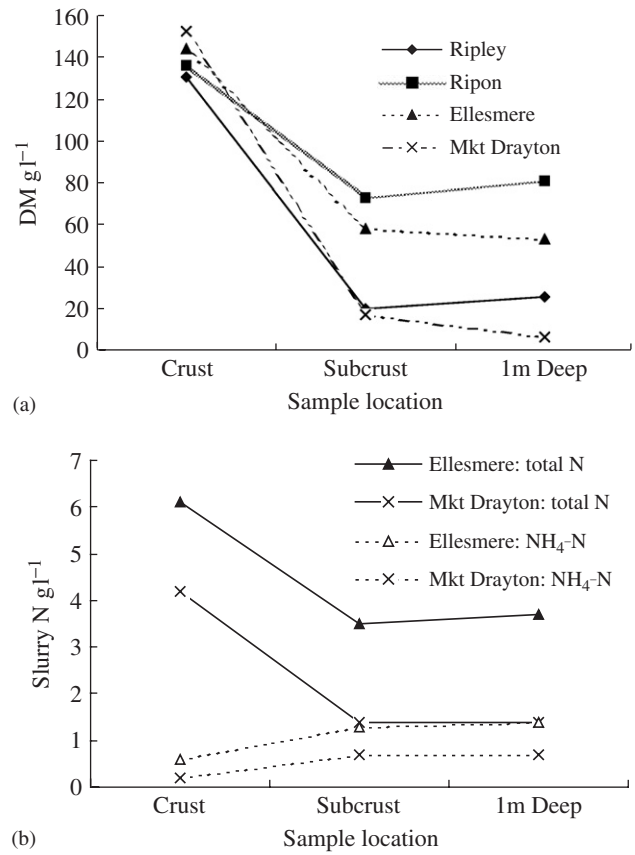

Fig. 3 – Analysis of slurry and crust samples collected using the inspection platform; data from four farms sampled at different depths, during 2002; (a) DM content from stores on 4 farms and (b) Total N and NH_4-N content in 2 farm stores.

[Fig. 2(b)], one an earth-banked lagoon and the other an above-ground tank, with no crust and also a high volume/surface area ratio (4.90 and 5.98, respectively), were on farms where slurry agitation was part of the regular management system.

3.2. *Slurry composition*

The crust and surface layers of the slurry were sampled and tested on a total of 7 farms and 9 stores using the hydraulic inspection platform. The examples shown in Fig. 3(a) and (b) are typical of the pattern observed across these sites and a number of observations can be made. (i) Crust DM content was within the range 12% and 15% and did not appear to be strongly related to the slurry DM content [Fig. 3(a)]. (ii) Below-crust slurry, at 0.5 m depth, often had a slightly lower DM content than slurry at greater depth, probably the result of rainfall draining through the crust and greater dilution at this point. (iii) Whilst a similar pattern is observed in slurry total N content, this is not the case with NH_4-N content, which has a greatly reduced concentration in the crust, reflecting loss of NH_3-N by volatilisation and, possibly, some leaching downwards in drainage through the crust [Fig. 3(b)]. Also, it is possible that some loss of NH_4-N may have occurred as a result of nitrification/denitrification within the crust. (iv) Mixing and homogenisation of the crust resulted in a much more uniform analysis at all sampling depths (results not shown here).

3.3. *Ammonia emissions*

Comparisons of emissions from uncrusted (disturbed) and crusted (undisturbed) areas of farm slurry stores were undertaken using the two vented cover-boxes. The disturbed areas occurred either where the crust was specifically disrupted, or where the crust had been disturbed during regular store filling, which in two cases was carried out immediately prior to the NH_3 emission measurements. These results are summarised in Table 1, together with those observations from both the small-scale and pilot-scale studies, where both crusted/non-crusted and disturbed/undisturbed slurry were present. In the case of crusted farm stores, some negative values occurred and are probably the result of low emissions from the crusted area and the relatively high background NH_3 concentrations due, either to emission from the disrupted store surface nearby, or other adjacent NH_3 sources.

For those experiments including direct comparisons between crusted and uncrusted slurry (3 small-scale, 12 pilot-scale and 6 farm-scale observations), the presence of a crust reduced the mean NH_3 emission rate by ca 60% over the duration of the observations. Results from the small-scale studies have been reported elsewhere (Misselbrook *et al.*, 2005) and only those data providing a direct comparison of

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Table 1 – Measurements of ammonia emissions from crusted and non-crusted slurry storage from farm-scale, pilot-scale and small-scale studies

Source	Measured NH_3-N emission, $g\,m^{-2}\,d^{-1}$				Δ emission %
	Observations (*n*)	Crusted	Observations (*n*)	Non-crusted	
Farm stores (floating covers)		0.03		0.01	0
		−0.36		1.66	122
		−0.18		1.31	114
		−0.10		0.76	113
		1.34		2.81	52
		−0.11		0.38	129
Small-scale studies					
		5.0		9.0	44
		5.9		13.2	55
		3.2		5.9	46
Pilot-scale studies unmixed/mixed[a]		3.05		8.27	63
		1.66		8.07	79
		0.65		6.75	90
		0.08		5.56	99
		3.21		5.51	42
		1.92		3.84	50
		1.21		3.02	60
		1.70		2.54	33
		1.63		2.53	36
		1.53		3.55	57
		1.58		2.86	45
Straw/unstrawed[b]		0.45		2.20	80
Means	(21)	**1.59**	(21)	**4.27**	63
Median		1.50		3.00	
St. dev.		1.70		3.33	

[a] Only thin crusts established on stores in pilot-scale studies; comparisons between mixed and unmixed slurry.
[b] In this pilot-scale study additional straw added to one treatment, resulting in well crusted slurry.

crusted and non-crusted slurry are included here, for completeness. Sommer *et al.* (1993), using small-scale storage tanks (ca $4\,m^3$), showed a natural crust on cattle slurry reduced emissions to 20% of those from stirred slurry. The reduction in these studies was less, possibly because the non-crusted slurry was agitated only in some cases and, where not agitated, did tend to develop a thin 'skin'. Mean emission rates from crusted slurries, ranged from 0.5 to $5.9\,g\,N\,m^{-2}\,d^{-1}$, comparing well with the value in the UK NH_3 emissions inventory for crusted cattle slurry stores of $1.7\,g\,N\,m^{-2}\,d^{-1}$ (range 0–$5.7\,g\,N\,m^{-2}\,d^{-1}$) (Misselbrook *et al.*, 2006). Emissions for non-crusted slurries were greater, ranging from 0–$13.2\,g\,N\,m^{-2}\,d^{-1}$. It was considered that measurements on small-scale tanks (ca $1\,m^3$), whilst satisfactory for comparative studies, would not be representative of real slurry stores and data from those should not be included in inventory emission factor (EF) estimates. Excluding these data, mean EF of 1.07 and $3.42\,g\,m^{-2}\,d^{-1}$ NH_3-N were derived, for crusted and uncrusted slurry stores, respectively.

In addition to reducing NH_3 emissions from stored slurry, the development of a surface crust also has the potential for oxidation of methane arising from the slurry (Petersen *et al.*, 2005). Measures to ensure crust formation therefore provide a cost-effective mitigation strategy for ammonia and greenhouse gas emissions.

3.4. *Factors affecting crust formation*

Whilst there was no evidence from the farm studies of a regional trend for crusting and possible climatic effects, detailed pilot-scale observations (summarised in Fig. 4) gave strong evidence of a climatic impact. In these observations it was clear that overall increases in crust thickness and strength were matched by the cumulative evaporative water loss from the tank. The studies also provided an indication that robust crusts (i.e. >ca 75 mm) are unlikely to form, until at least 250 mm of evaporative loss had occurred from the surface of the slurry. However, anecdotally, crusts are also known to form on slurry within covered storage tanks.

The importance of slurry solids content was indicated both in the small-scale and the farm-scale studies. The nature of the slurry solids content may also be important—large differences were observed in crust formation on slurries from cattle fed maize or grass silage, although these results are not

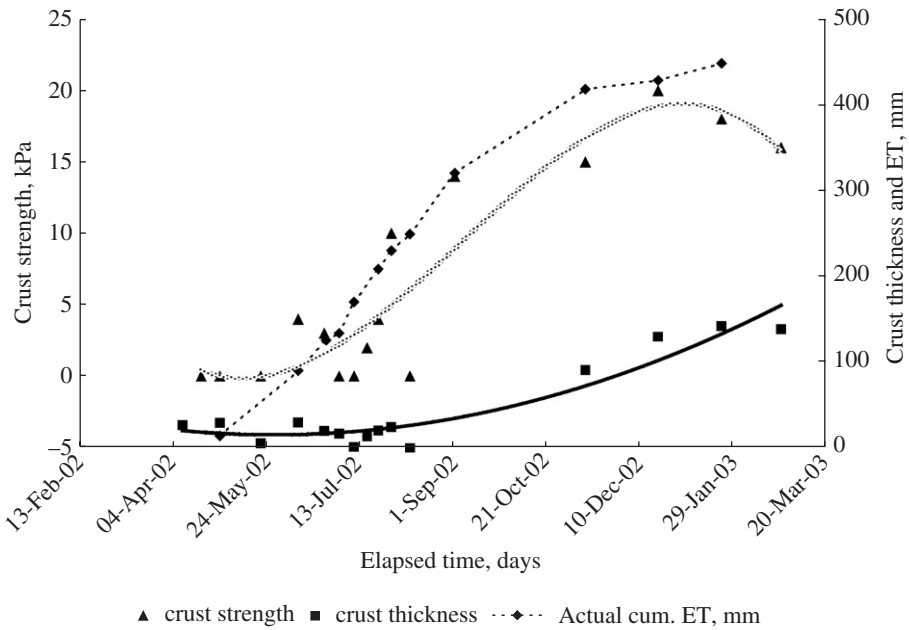

Fig. 4 – Example of changes in crust thickness and strength with time; pilot-scale studies at Silsoe Research Institute; ET, Evapotranspiration.

reported here. Crusts do not occur on pig slurry stores, the solids normally settling rapidly and forming a dense sludge layer towards the base of stores (Chambers, 2004). However, the addition of finely chopped straw has been effective in establishing a crust on stored pig slurry in Denmark.

The pilot-scale studies supported the hypothesis that deeper tanks (with increased volume/surface area ratios) would sustain the thickest and strongest crusts, due to the greater availability of crust forming material beneath the exposed surface. These results were consistent with the observed farm-scale data [Fig. 2(b)], in which increasing the volume/surface area ratio was associated with increasing incidence of crusting.

3.5. *Slurry crust assessments*

During assessment of crust characteristics, the force-plate penetrometer tended to push the crust into the slurry, in cases where the crust was relatively thin. Thicker crusts imparted greater rigidity towards downward pressure, thus allowing penetrometer measurements to more accurately reflect penetration resistance. In order to draw comparisons across a range of crust thicknesses, downward pressure was maintained and steadily increased, until a complete penetration of the crust was achieved and the maximum pressure was then recorded. At one site, high moisture content in the crust, due to recent rainfall, was found to substantially reduce the penetration resistance. In this paper, results from dry crusts only are reported. Using this methodology, an approximate 1:1 relationship was found where assessments were carried out on sawdust-based slurry storage on seven farms, with crust strength (kPa) increasing with crust thickness

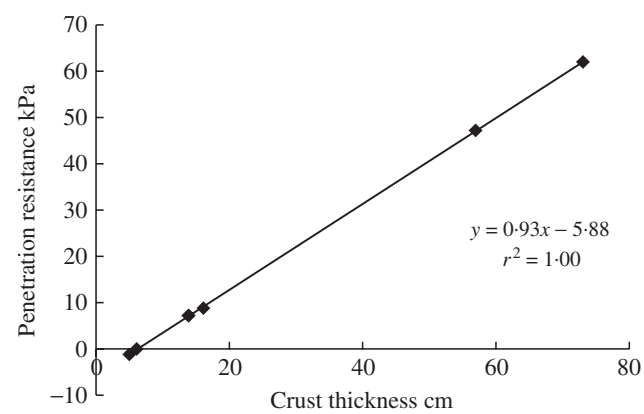

Fig. 5 – Assessment of crust penetration resistance on above-ground slurry storage (sawdust-based slurry systems), results from seven farm sites, December 2000–May 2002; assessments using force-plate penetrometer; r^2, coefficient of determination.

(probability $P<0.05$; coefficient of determination $r^2 = 1.00$) over a range of 0–73 cm (Fig. 5).

Crust 'integrity' tests were carried out using the falling weight technique on two areas within one farm store, one with a thick, dense crust and the other, where the crust was looser and thinner. A strong linear relationship between penetration depth and fall distance was found in both cases on crusted slurry in a sawdust based system (for thick, dense crust $P<0.05$; $r^2 = 0.99$; for loose crust $P<0.05$; $r^2 = 0.80$) [Fig. 6(a) and (b)]. Similar observations on another farm with a straw-based slurry system suggested, not surprisingly, that crusts containing

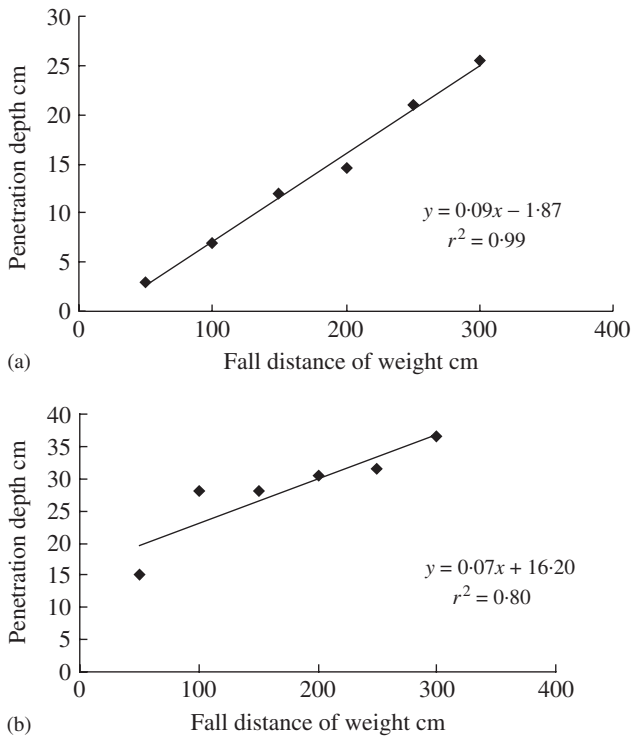

Fig. 6 – Crust penetration on thick and thin slurry crusts from a sawdust-based slurry system; assessments using the falling weight technique. Observations at farm site, Betley, Cheshire, January 2002; r^2, coefficient of determination.

chopped straw bedding material are rather stronger per unit thickness.

4. Conclusions and recommendations

About 80% of slurry stores were found to be crusted during an initial study of 50 dairy farms across major dairying areas in England. Regular slurry agitation was carried out by almost 70% of farms.

Formation of a natural crust on cattle slurry stores reduced NH_3 emission by approximately 60%. This confirms the significant potential for crusting to reduce NH_3 from stored slurries reported earlier by Sommer *et al.* (1993). The results suggest that natural crusts have important potential for emission abatement at neutral-low cost to the farmer and have confirmed the benefits of crusting under practical farm conditions. However, measurements of NH_3 emissions during crust destruction should also be carried out, to ensure that the benefits of NH_3 retention during storage are not subsequently lost in this final phase as the store is mixed and homogenised prior to emptying. If natural crusting is to be included as an option for reducing emissions from stored slurries, an objective assessment of crust integrity needs to be developed to assist with effective policy implementation. A type of 'crustometer' could be developed, at least partly based on the falling weight technique described and tested briefly within the field studies.

A number of conclusions can also be drawn about the factors influencing crust formation:

- It was clear that slurry solids content had an important impact on crust formation – crusts did not form on slurries with a DM content of <1%.
- Crust thickness was related to cumulative evaporation of water from the surface of the slurry. The results suggested that robust crusts (i.e. >75 mm thickness) did not develop until at least 250 mm of evaporative loss had occurred.
- Slurry stored in tanks with low volume/surface area ratios tended to produce crusts rapidly, probably as a result of rapid evaporative loss from the slurry surface. Stores with high values of the ratio eventually produced thicker, stronger crusts, although this could take months to occur, due to slow evaporative loss from the limited surface area.

Although these studies have highlighted factors contributing to crust formation, their relative importance is unclear. Improved understanding of the crusting process might be regarded as of low importance given the high incidence of crusting on farm slurry stores both within this study and from general experience. However, further understanding would help with aspects of crust management and, in particular, how crust formation can be encouraged where not normally anticipated (e.g. in pig slurry). Further studies should cover key factors, including the content and nature of slurry solids, particle size distribution, solution viscosity and resistance to water loss, slurry gasification and surface evaporative losses. An improved understanding would facilitate the development of a modelling approach for the prediction of crust development and, hence, likely emission abatement efficiency. In particular, the model should aim to take into account rainfall, evaporative losses and slurry solids content, with some consideration also of the impact of animal diet and bedding material in the slurry system. The model would have a practical application for the industry in providing advice on best management strategies for mitigation of gaseous emissions.

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