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Desorption

EQUILLIBRIUM MOISTURE CONTENT (EMC) OF STRAW

Greg Swain

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PREFACE

In the last few years the interest in using straw for other purposes than the traditional ones has increased. In many quarters plans are being made in order to use straw as solid fuel. One condition for obtaining good results is then that the supply of straw is guaranteed every season which means that a final drying of the straw might be necessary. This must be done in an inexpensive way, i.e. by means of cold air. To be able to make the drying as effective as possible it is important to know the relation between the moisture content of the straw and the relative humidity and temperature of the surrounding air. Information of this kind is, however, in general not available and therefore the Swedish Institute of Agricultural Engineering applied to the Royal Academy of Agriculture and Forestry for funding in order to make an introductory investigation into this matter. The results from the investigation are presented in this report.

The investigation was planned and conducted by Senior Research Manager Nils Ekström. The experimental work was done by Greg Swain, B.Sc.Agr.Eng., from Raleigh, USA, who also analysed the results and prepared the report. In performing his task Greg Swain also took advice from Research Manager Gunnar Lundin. The graphs were drawn by Kim Gutekunst.

To all who have contributed to the accomplishment of the investigation we want to express our sincere appreciation.

Ultuna, Uppsala, November 1984

Björn Sundell	Olle Norén
Director	Head of Research

Acknowledgements

The author wishes to thank the staff at JTI for the opportunity to work and learn with them. Special thanks to Nils Ekström and Gunnar Lundin for their guidance and support. Thanks also to Håkan Adefjord for his photography, Kim Gutekunst for art work, and to Dr. C.W. Suggs, N.C. State University, USA, for his review of this paper.

Greg Swain

CONTENT

LITERATURE REVIEW

Many investigations have resulted in data and curves for equilibrium moisture contents of grain and hay. However, little work has been done in this field with straw, since it has only recently become important to know its EMC. Duggal and Muir (1981) discussed results of a study of adsorption EMC for wheat straw. The main goal in this study was to fit available mathematical models for kernels to their experimental data for straw. No further tests were made with straw of different grains or of different maturities; only the temperature was varied for different relative humidities. Studies in Finland were carried out for straws of barley, oats, rye, winter wheat and spring wheat at four different humidities and temperatures (Ahokas et al, 1983). This study concluded that the EMC's of straws from barley, rye, and wheat were too similar to distinguish (differences from 0.0 - 0.8 % units), and these results were combined into one EMC curve at each temperature. Separate curves were given for oat straw, but at only two temperatures due to the uncertainty of the results. Finnish investigation was published after the JTI-trials were planned.

The desire to develop individual EMC curves for straws of particular grains and to study the effect of straw maturity, as well as to verify previous results, encouraged a further investigation of straw EMC.

EMC-DETERMINATION

Materials

Straw from barley, oats, and winter wheat was evaluated. Samples were taken from the windrow after combining for grain investigations (Fig. 1). Each type of straw was collected at several different stages of maturity, based on the moisture content of the grain (Table 1).

BACKGROUND AND AIM

A few years ago only a small portion of the straw produced in Sweden was used in farming. Cattle feed and animal bedding were the main fields of application. When such small amounts of straw were used, it was - as a rule - possible to harvest the straw at a sufficiently low moisture content, despite unfavourable weather conditions during the harvesting season.

The so-called energy crisis during the last decade has caused a large interest in straw as an energy resource. However, the investments for straw-burning plants are rather high, and thus the plant owners must be assured that they will receive adequate amounts of good straw. This means that the available straw should have a sufficiently low moisture content (18-20 %) to allow storage for several months without moulding. Straw can also be briquetted, which improves the handling and combustibility, and decreases transport volume problems. Most briquetting machines allow a maximum moisture content of about 18 % for effective use. To achieve these moisture contents in the Swedish climate, the straw would, in some years, have to be artificially dried.

Straw used as fuel must be as cheap as possible. Thus, the straw should be dried in simple cold-air dryers similar to the model that JTI studied a few years ago (JTI Report No. 64). If used efficiently the dryer's fan is run only when the air is dry enough to remove moisture from the straw. This condition is determined by the equilibrium between the moisture content of the straw and the relative humidity of the air. The equilibrium moisture content (EMC) is defined as "the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time" (Brooker et al, 1979). The EMC of a particular material is dependent upon the humidity and temperature of the environment at a given time, as well as on the species, variety, and maturity of the material.

The purpose of this report is to describe and present the results of an investigation into the desorption equilibrium moisture content in straw. Comparisons were made between different species and maturities of straw, as well as between different humidities and temperatures. From these trials practical equilibrium moisture curves were developed. Data was also collected for natural and simulated field drying.

Table 1. Straw used in the EMC trials (m.c. = moisture content in % wet basis)

Type straw	Variety	Harvest date	No.	Grain m.c. at harvest	Straw m.c. at harvest and at the start of EMC trials at 20°C	Initial m.c. of frozen straw for EMC trials at 20°C	Initial m.c. of frozen straw for EMC trials at 10°C
Barley	Birka	20/8	1	34	60.3		
		22/8	2	27	50.4		50.8
		24/8	3	23	45.2	47.9	
		29/8	4	19	34.5	37.8	42.7
Oats	Selma	27/8	1	27	60.5		64.8
		2/9	2	23	62.6		
		7/9	3	20	54.0	48.8	57.1
Winter wheat	Holme	1/9	1	27	43.3		
		6/9	2	23	37.1	34.9	31.9
		17/9	3	35	32.1		

Fig. 1. Example of windrowed straw (oats). Photo G. Swain.

An initial large sample was taken from the field and later divided into smaller samples as follows:

1. Fresh straw for the EMC investigation at 20°C.
2. Frozen straw for the EMC investigation at 20°C (to compare with fresh straw results).
3. Frozen straw for the EMC investigation at 10°C.
4. Fresh straw for the simulated field drying investigation (described later).

Fresh straw was used immediately, and the rest was frozen for later trials.

The relative humidity and temperature were determined for each chamber at least once a day using the Assmann-psychrometer. In addition, a thermohygrograph was placed in each chamber (Fig. 3).

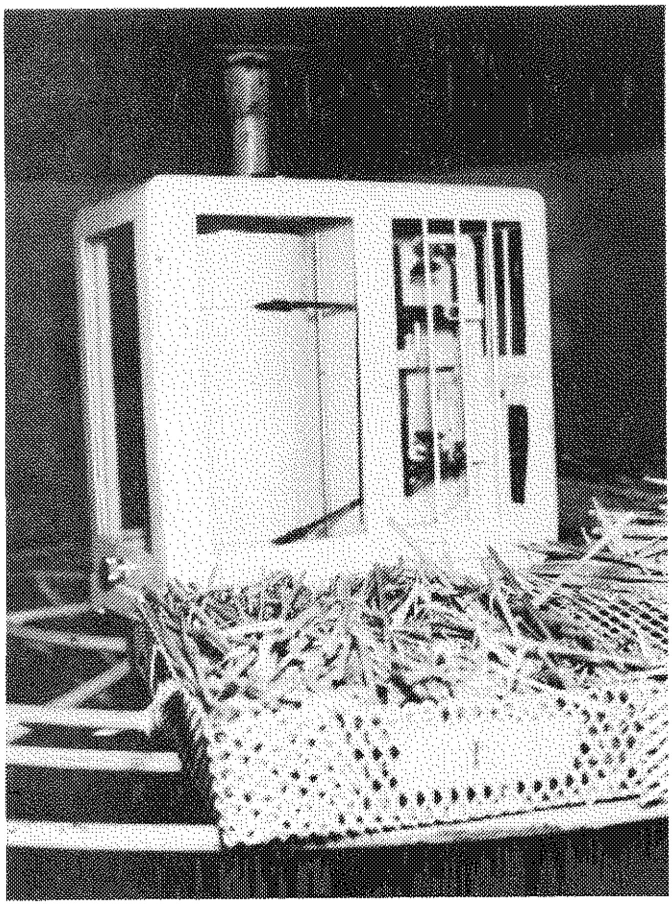

Fig. 3. Thermohygrograph and straw samples inside the chamber. Photo H. Adefjord.

Although these instruments were not accurately calibrated for relative humidity, they were useful in showing changes in both the relative humidity and temperature (Fig. 4).

METHOD

Test samples of straw from barley, oats, and winter wheat were stored in four 1 m^3 sheet metal chambers with controlled air humidity (Fig. 2). The air was internally circulated by small fans. The chambers were placed in the same room where the temperature was regulated by thermostats. The relative air humidities were controlled by passing the air across saturated salt solutions. The following salts were used to obtain the corresponding relative humidities at 20°C (approximately):

Sodium Carbonate $Na_2CO_3 \cdot 10H_2O$	92 % r.h.
Sodium Chloride NaCl	76 % "
Calcium Nitrate $Ca(NO_3)_2 \cdot 4H_2O$	55 % "
Calcium Chloride $CaCl_2 \cdot 6H_2O$	35 % "

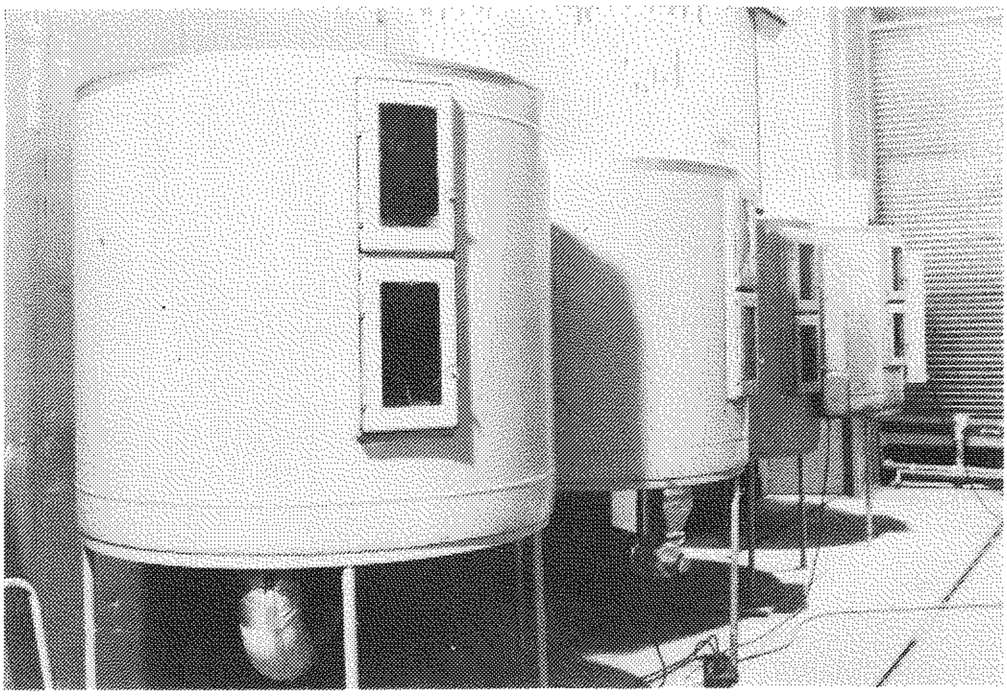

Fig. 2. Chambers used in EMC trials. Photo H. Adefjord.

Silicon gel was also used at times to help control the humidity of the 55 and 35 % chambers. Another required adjustment was to maintain the room temperature about 1°C lower than the desired chamber temperature, due to heating by the small fans.

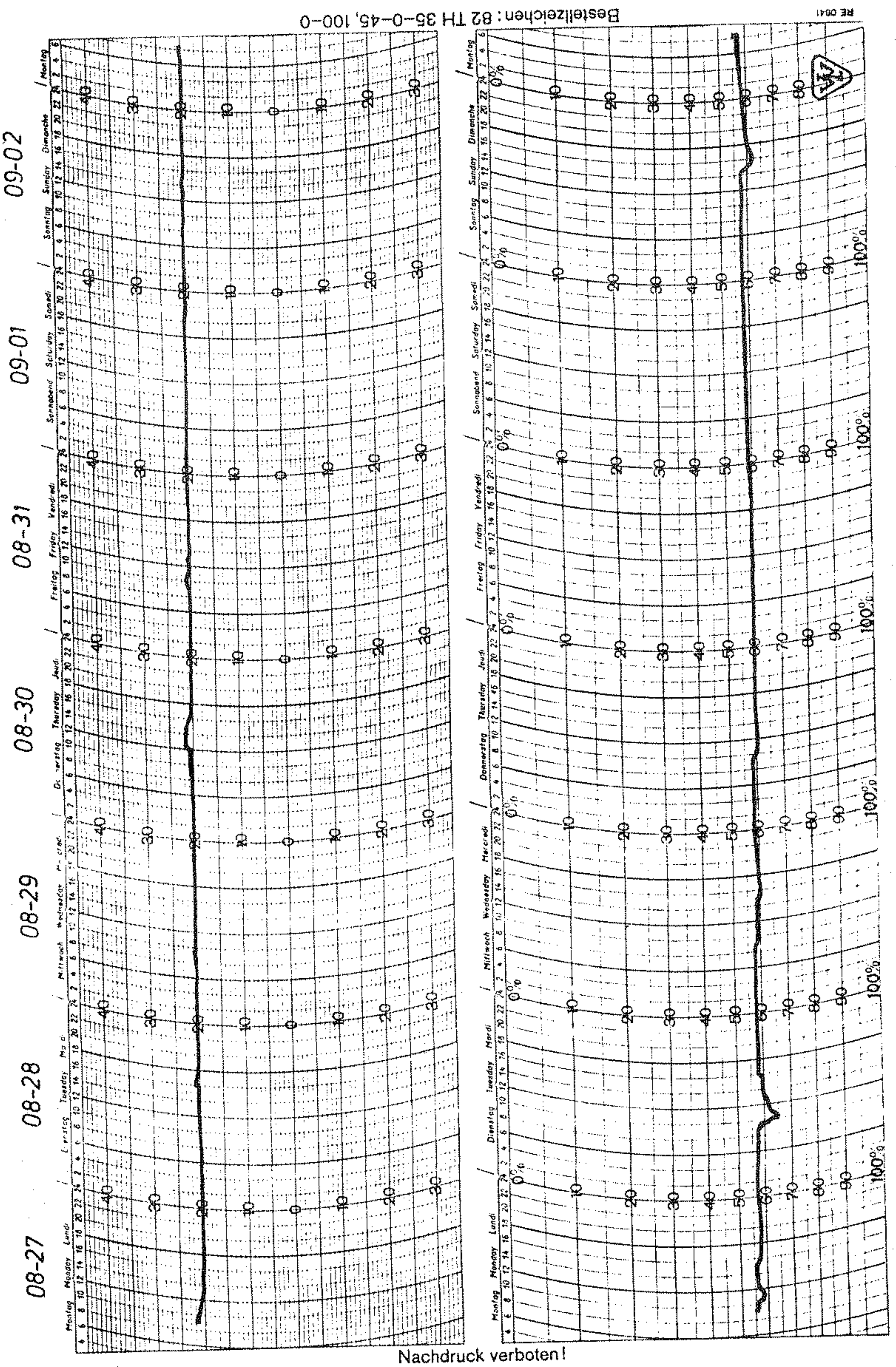

Fig. 4. Recording of relative humidity and temperature for 55 % relative humidity chamber.

Each sample was taken out individually and weighed once a day (Fig. 6). When the weight reached a constant value, the sample was removed and its moisture content determined by the method described earlier.

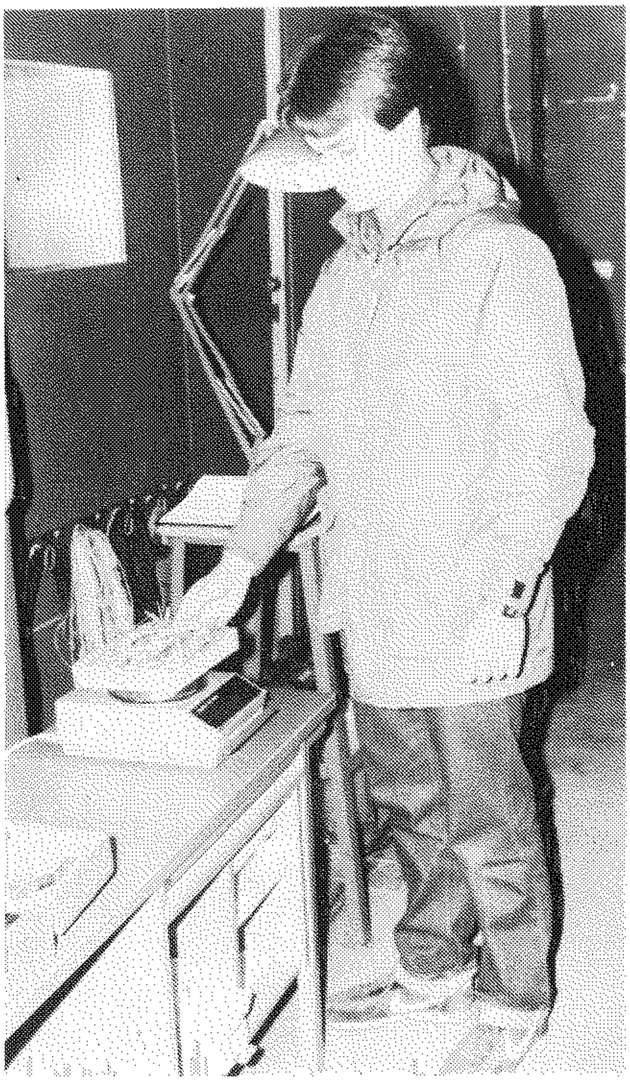

Fig. 6. Each sample was weighed once a day. Photo H. Adefjord.

Comparison of fresh and frozen straw

When all 20°C samples were removed, a trial was repeated at 20°C, but with samples which had been frozen. The samples had been stored at about -18°C in polyethylene bags. They were removed from the freezer the day before being prepared to allow precipitated moisture to readsorb into the straw. Nevertheless, as seen in Table 1 there were some differences between the moisture contents in the fresh and the frozen straw. Samples were used from 2 barley, 1 oat, and 1 winter wheat harvest.

EMC-Determination at 20°C

The initial EMC trials were conducted at 20°C. Straw samples were used from 4 barley, 3 oat, and 3 winter wheat harvests, each at a different maturity. A portion of the fresh sample was chopped and used to determine the initial moisture content of the straw. All moisture contents were determined by using the standard JTI process of three parallels, dried at 105°C for 3 hours. All moisture contents were reported on a wet mass basis.

Fig. 5. The straw samples for EMC trials were prepared by cutting into suitable pieces. Photo G. Lundin.

The chamber samples were prepared by cutting the straw to about 200 mm lengths (Fig. 5). Straw samples of about 30-50 g were placed in individual expanded metal trays, after the tray's tare weight was recorded. The total weight of tray and sample was recorded, and three samples were immediately placed in each chamber (Fig. 3).

As shown by the curves for barley, oats, and winter wheat, the maturity of the straw generally resulted in negligible differences in EMC. The most notable differences occurred with oat straw, which was the most variable of the straws for all trials. However, for the desired moisture content of about 18 %, the curves showed a maxium difference of only 2-3 % in relative humidity to obtain the same moisture content level. Simplified curves were therefore drawn, forming a composite or mean curve from the individual curves of different maturities. The composite curves are shown for barley, oat, and winter wheat straw at both 20 and 10°C (Fig. 13-15). Table 3 lists the values plotted in Figures 13-15.

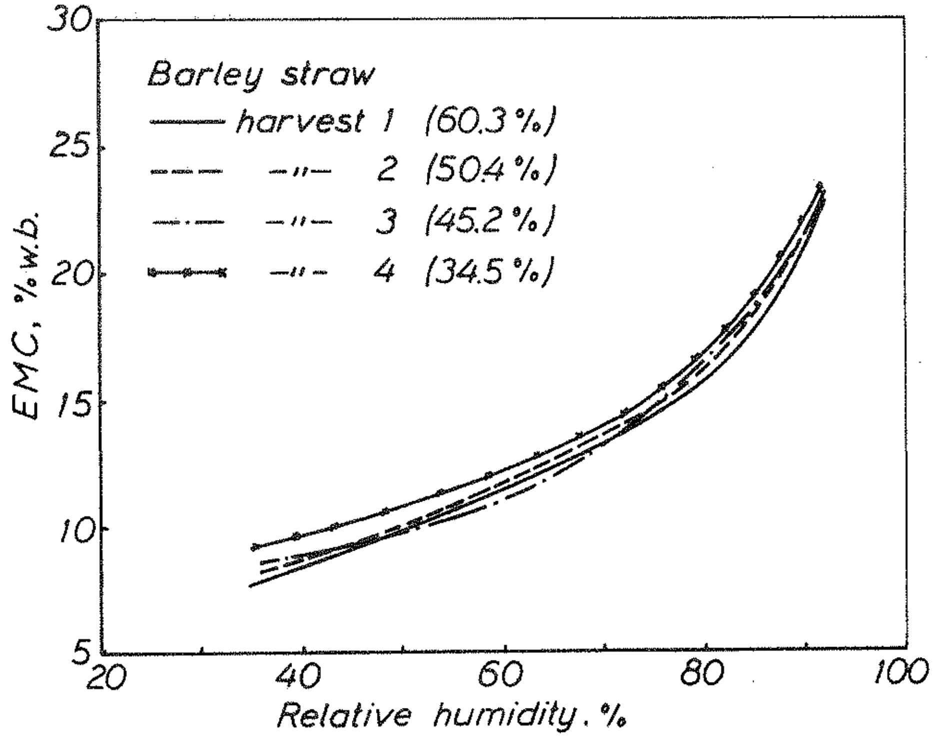

Fig. 7. EMC-curves for barley straw of four different maturities. Temperature 20°C.

The purpose of this trial was to compare the EMC's of fresh and frozen straw. It was suspected that the desorption, or ability to lose water, may not be the same for straw that has been frozen. If the resulting EMC's were determined to be adequately similar, then the frozen straw could be used for EMC trials at 10°C. Because of the favourable results (discussed later), frozen straw was useful in the EMC trials at 10°C.

EMC-Determination at 10°C

Since each EMC curve is defined at a specific temperature, a 10°C trial was conducted to give results over a practical range. The samples were frozen as described earlier. Only samples from 2 barley, 2 oat, and 1 winter wheat harvest were used, due to lack of space and to the similar results between different maturities in the 20°C trial.

As noted earlier, the expected relative humidities for the salt solutions used were valid for 20°C. Thus, the relative humidites at 10°C were slightly different.

RESULTS

The EMC values

The data which was collected during the EMC trials was used in several comparisons. The primary goal was to develop EMC curves which could be used for cold-air drying of straw. However, other factors were considered, both to make the results more extensive and useful, and also to justify conclusions which would simplify the results.

Since no previous investigations had dealt with EMC differences between different maturity stages, the samples from each harvest were compared, for each type of straw at 20°C (Fig. 7-9 and Table 2). Separate EMC curves are also shown for 10°C (Fig. 10-12 and Table 2).

Table 2. Observed desorption equilibrium moisture contents (EMC) at 20°C and 10°C

Type straw	Harvest No.	Mean EMC at 20°C for fresh straw				Mean EMC at 20°C for frozen straw				Mean EMC at 10°C for frozen straw			
		Approx. rel. humidity, %											
		92	76	55	35	92	76	55	35	93	75	59	38
Barley	1	22.9	14.5	10.6	7.6								
	2	23.5	14.7	10.8	8.2					29.4	16.6	13.9	10.0
	3	22.8	14.7	10.2	8.6	21.6	14.4	11.8	8.8				
	4	23.1	15.0	11.4	9.1	21.2	15.1	11.8	8.6	27.2	16.0	13.4	9.6
Oat	1	29.3	16.8	11.1	8.7					33.8	16.9	13.1	10.1
	2	25.9	15.7	11.2	7.9								
	3	24.7	15.5	10.7	7.4	24.8	15.5	11.9	8.7	30.2	16.4	13.0	9.7
Winter wheat	1	23.6	15.5	11.0	7.7								
	2	22.6	15.1	11.2	7.6	22.9	14.8	11.3	7.8	27.9	15.7	12.8	9.3
	3	21.8	15.3	10.6	7.2								

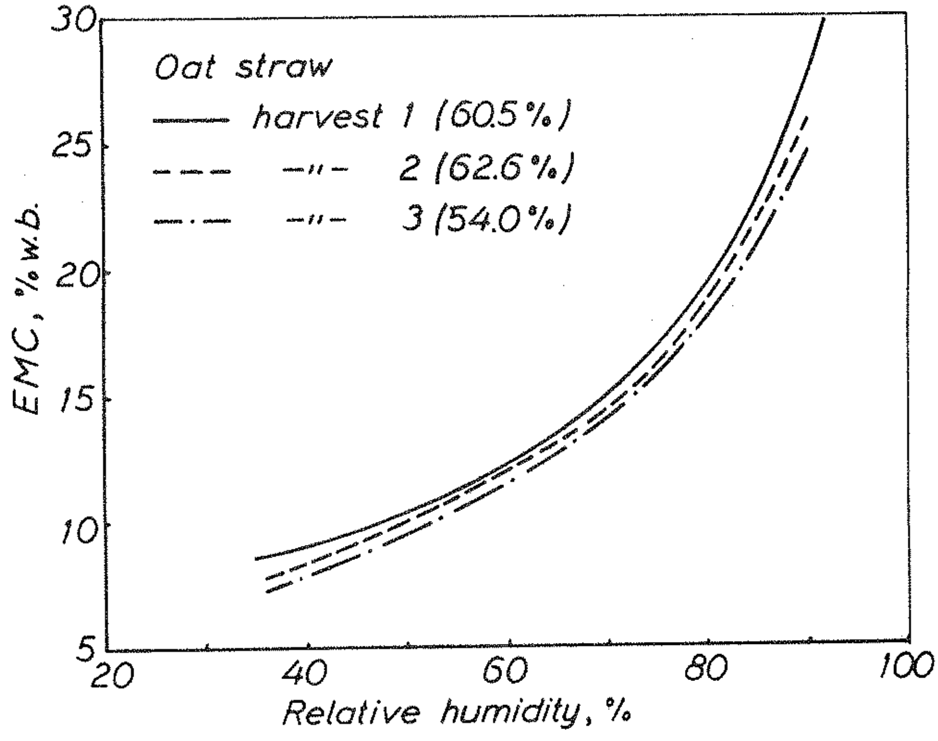

Fig. 8. EMC-curves for oat straw of three different maturities. Temperature 20°C.

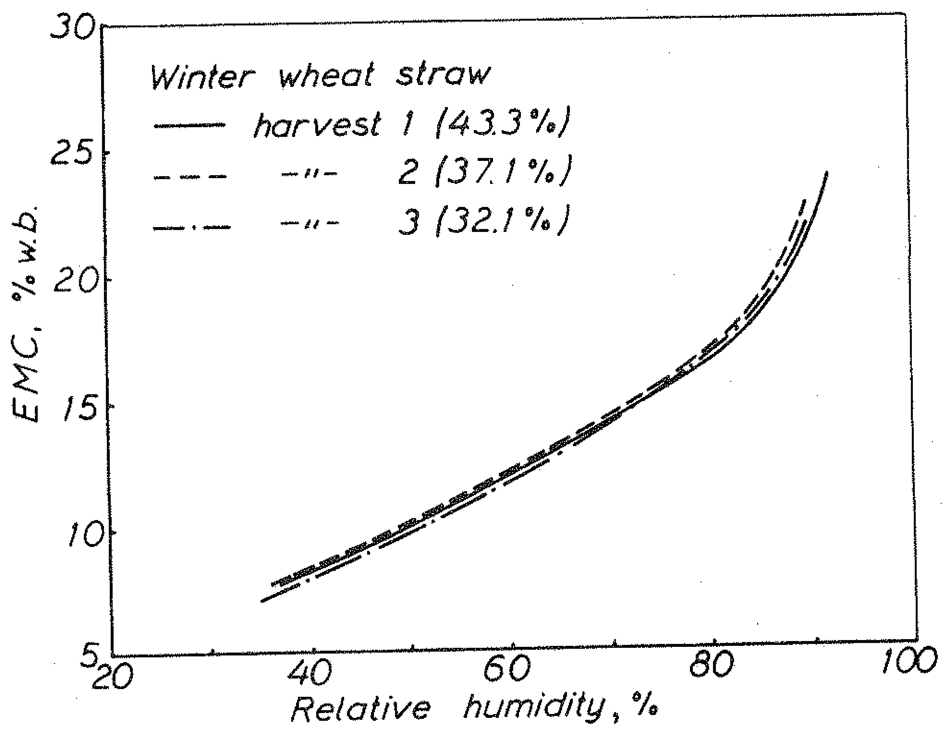

Fig. 9. EMC-curves for winter wheat straw of three different maturities. Temperature 20°C.

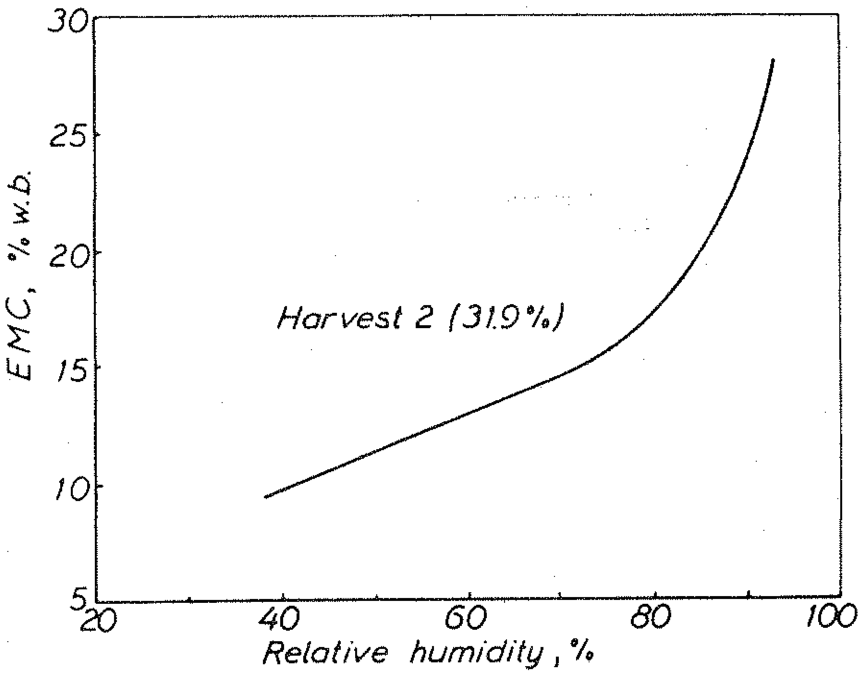

Fig. 12. EMC-curve for winter wheat straw of one maturity. Temperature $10^{o}C$.

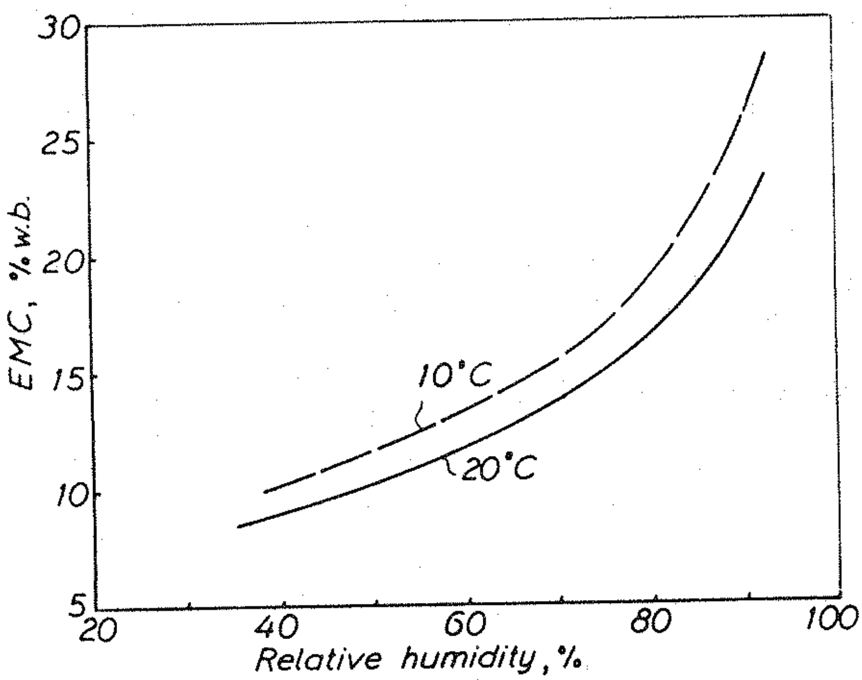

Fig. 13. Composite of EMC-curves for barley straw at $10^{o}C$ and $20^{o}C$ respectively.

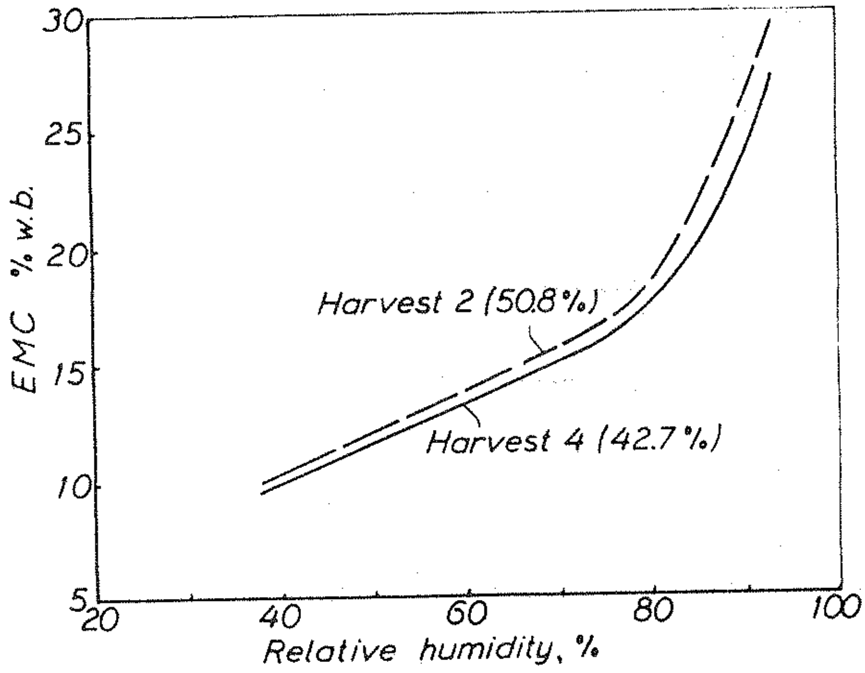

Fig. 10. EMC-curves for barley straw of two different maturities. Temperature 10°C.

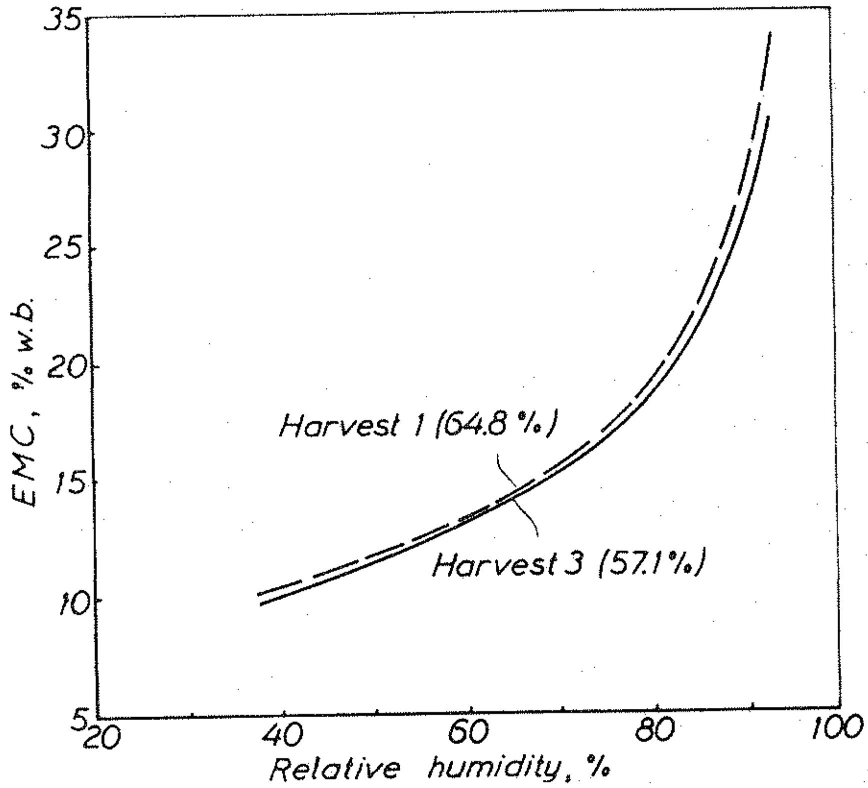

Fig. 11. EMC-curves for oat straw of two different maturities. Temperature 10°C.

Table 3. Mean EMC of straw harvested at different maturities.

Straw	Temperature °C	No. Harvests	Rel. Hum. Mean, %	EMC %
Barley	20	4	92.0	23.1
			75.3	14.7
			54.8	10.8
			35.5	8.4
	10	2	93	28.3
			75	16.3
			59	13.7
			38	9.8
Oat	20	3	90.7	26.6
			74.3	16.0
			55.3	11.0
			35.7	8.0
	10	2	93	32.0
			75	16.7
			59	13.1
			38	9.9
Winter wheat	20	3	90.7	22.7
			75	15.3
			55.3	10.9
			36	7.5
	10	1	93	27.9
			75	15.7
			59	12.8
			38	9.3

Factors affecting the results

The curves comparing fresh and frozen straw at 20°C were also quite similar (Fig. 16-19, Table 2). The widest variation was again between the oat straw samples. However, even these curves were basically the same above 70 % relative humidity. These results therefore justified using frozen straw for the 10°C trials.

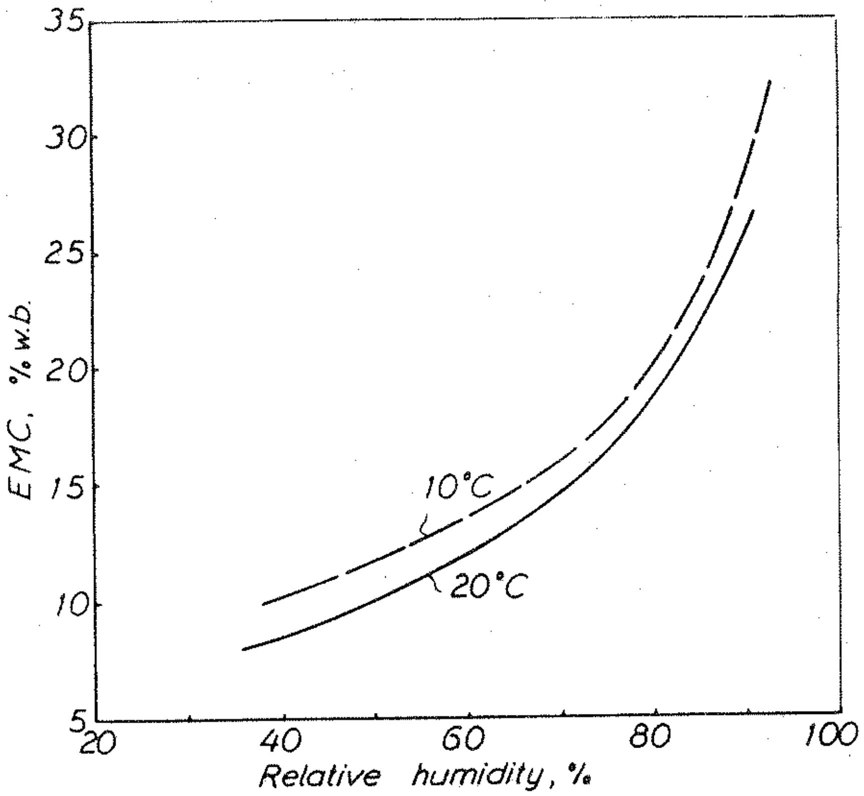

Fig. 14. Composite of EMC curves for oat straw at 10°C and 20°C respectively.

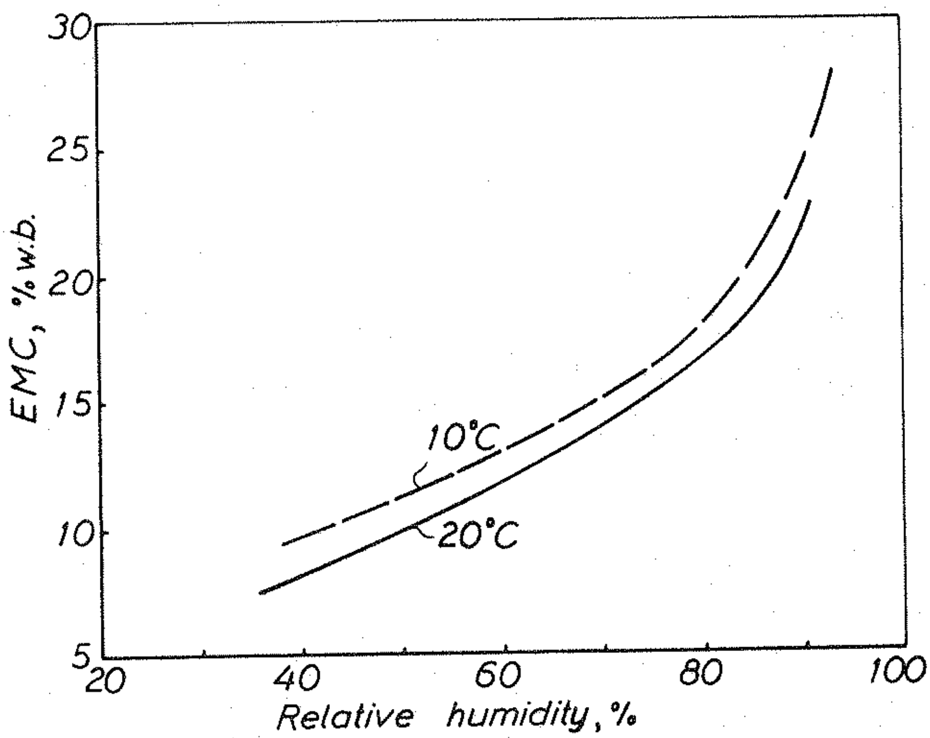

Fig. 15. Composite of EMC curves for winter wheat straw at 10°C and 20°C respectively.

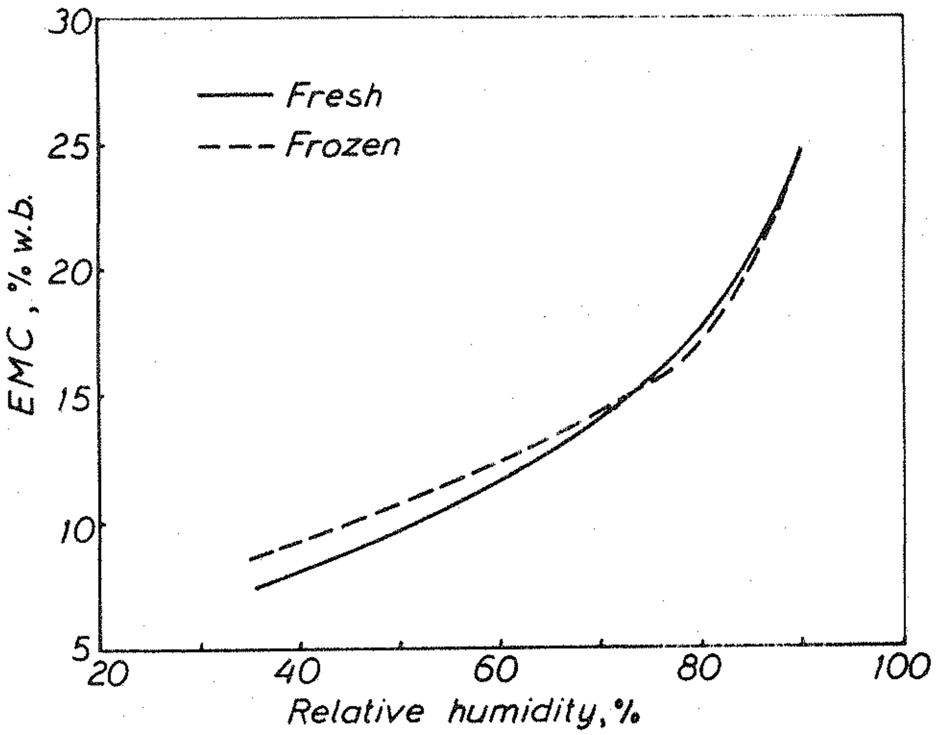

Fig. 18. Comparison of EMC for fresh and frozen oat straw at 20°C (third harvest at 54.0 % initial m.c.).

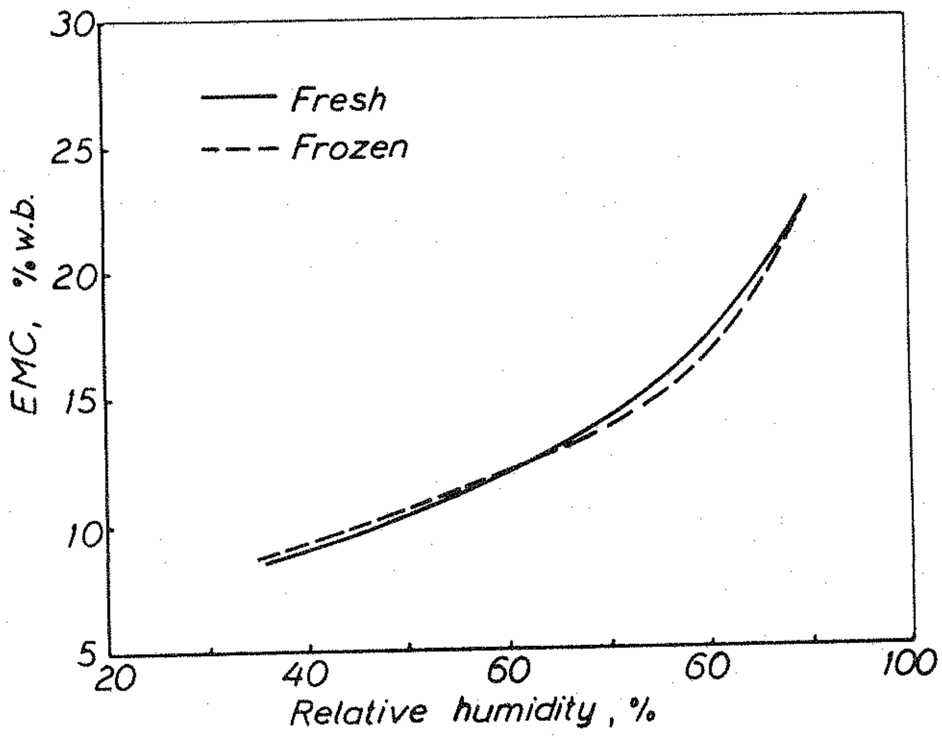

Fig. 19. Comparison of EMC for fresh and frozen winter wheat straw at 20°C (second harvest at 37.1 % initial m.c.).

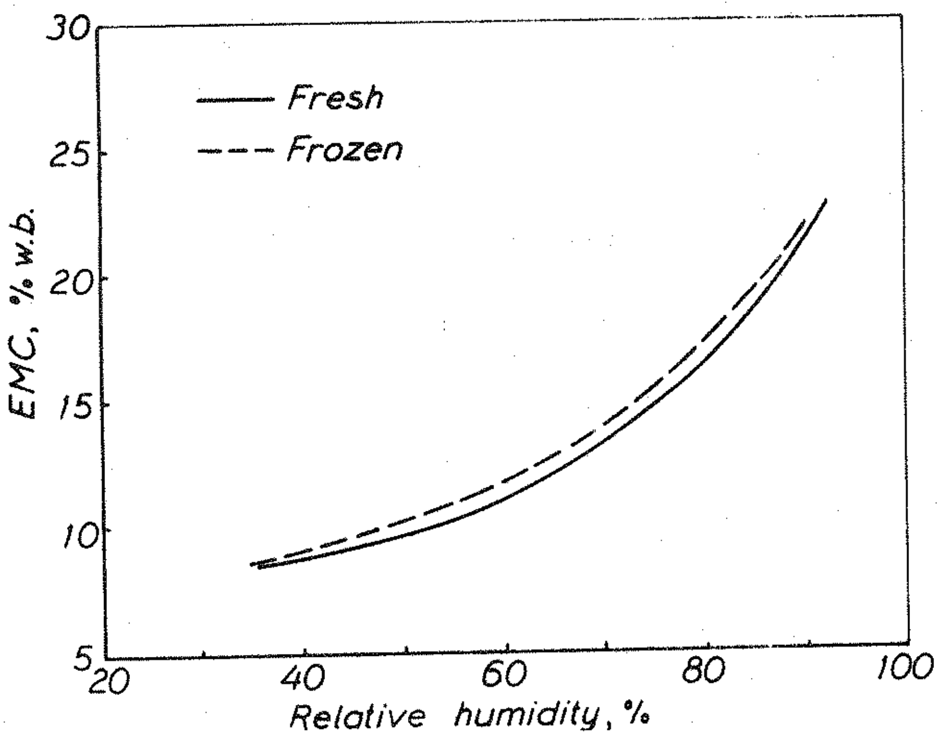

Fig. 16. Comparison of EMC for fresh and frozen barley straw at 20°C (third harvest at 45.2 % initial m.c.).

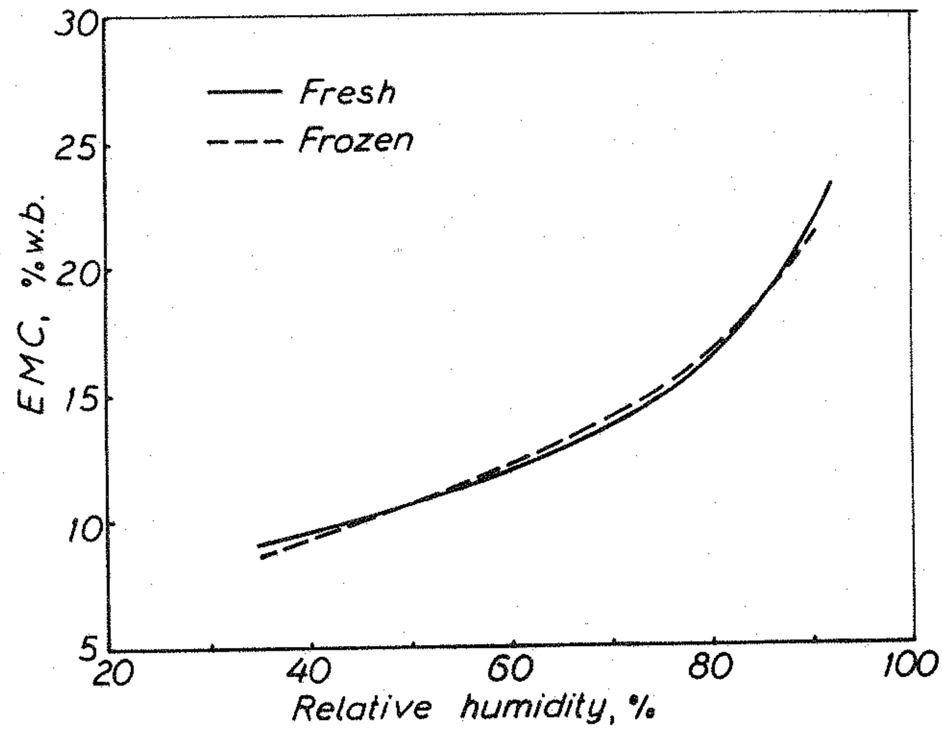

Fig. 17. Comparison of EMC for fresh and frozen barley straw at 20°C (fourth harvest at 34.5 % initial m.c.).

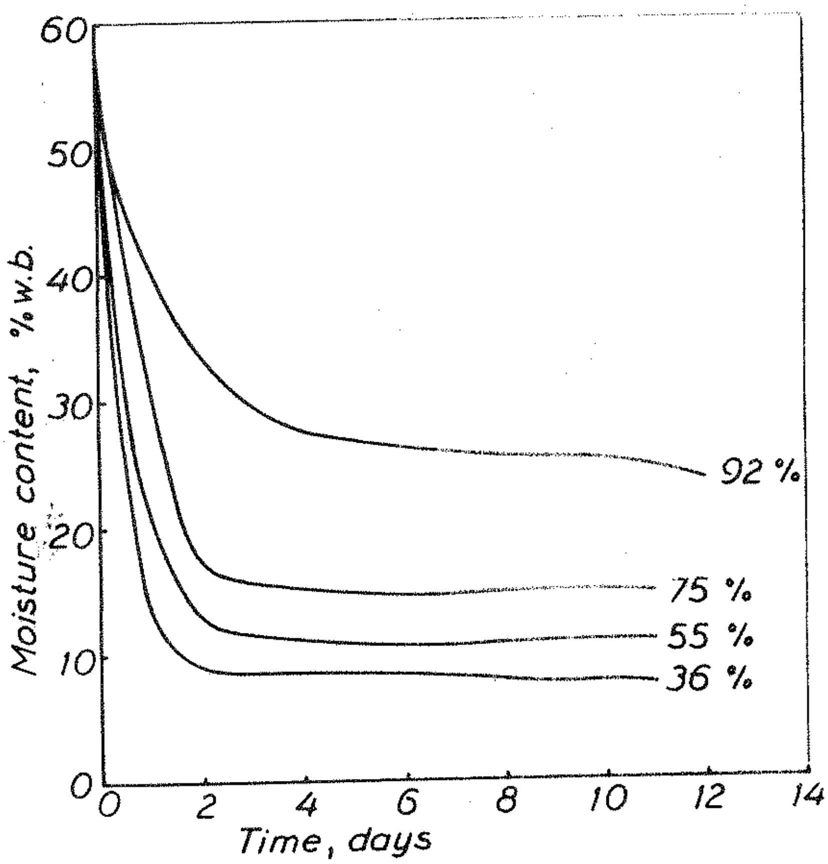

Fig. 20. Moisture content change over time in barley straw, kept in air of different humidities. Harvest 1, 60.3 % initial m.c.

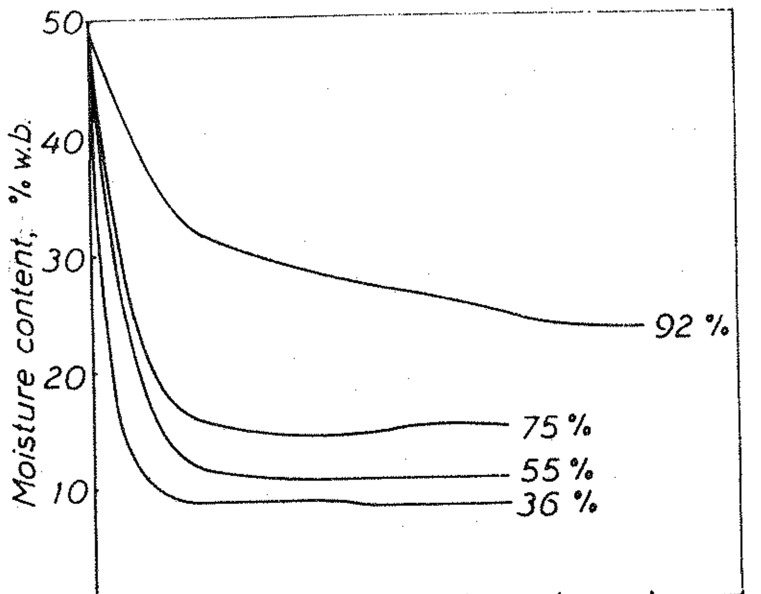

Fig. 21. Moisture content change over time in barley straw, kept in air of different humidities. Harvest 2, 50.4 % initial m.c.

There were some difficulties in determining the EMC during the trials. The majority of problems involved the chamber with 92 % relative humidity. In some cases, at both temperatures, it was difficult to determine when the samples had reached their EMC. Some samples continued to lose small amounts of weight 12-14 days after being placed in the chambers. However, these losses were eventually considered to be due to dry matter losses, and the samples were removed and their moisture contents determined.

In the highest humidity chamber, small amounts of mould were found on the oat straw samples at 10°C. However, the degree of mould growth was so small that the trial was continued using these samples.

Moisture content development

Further calculations were made using data from the EMC trials. The daily weight and final moisture content of each sample were used to follow the changes in moisture content. These results showed that the development of the moisture content was slightly influenced by changes in the chamber environment. It was also notable that these calculated initial moisture contents differed from the corresponding figures in Table 1. Factors such as variations in the initial sample, and dry matter losses during testing account for the small disagreements. Despite these differences, the curves (Fig. 20-29) present a vivid picture of how fast the moisture content drops during different conditions.

The curves relate moisture content and time for all harvest samples at 20°C. One relationship these curves demonstrate is the difference in the rate of moisture loss for particular relative humidities. For instance, Fig. 20 shows that it took about 8 days to reach a moisture content within about 2 % units of the EMC at 92 % relative humidity. However, at 76 % it took only about 2 days before the moisture content was within 2 % of the final EMC.

These curves can also be used to compare rate of moisture loss between the different types of straw. Fig's 24-26 clearly show that oat straw is much more gradual in its moisture loss than either barley or winter wheat straw. For example, it generally took about 4 days to reach an approximate EMC at 76 % relative humidity with oat straw, compared to about 2 days for barley and winter wheat under the same conditions.

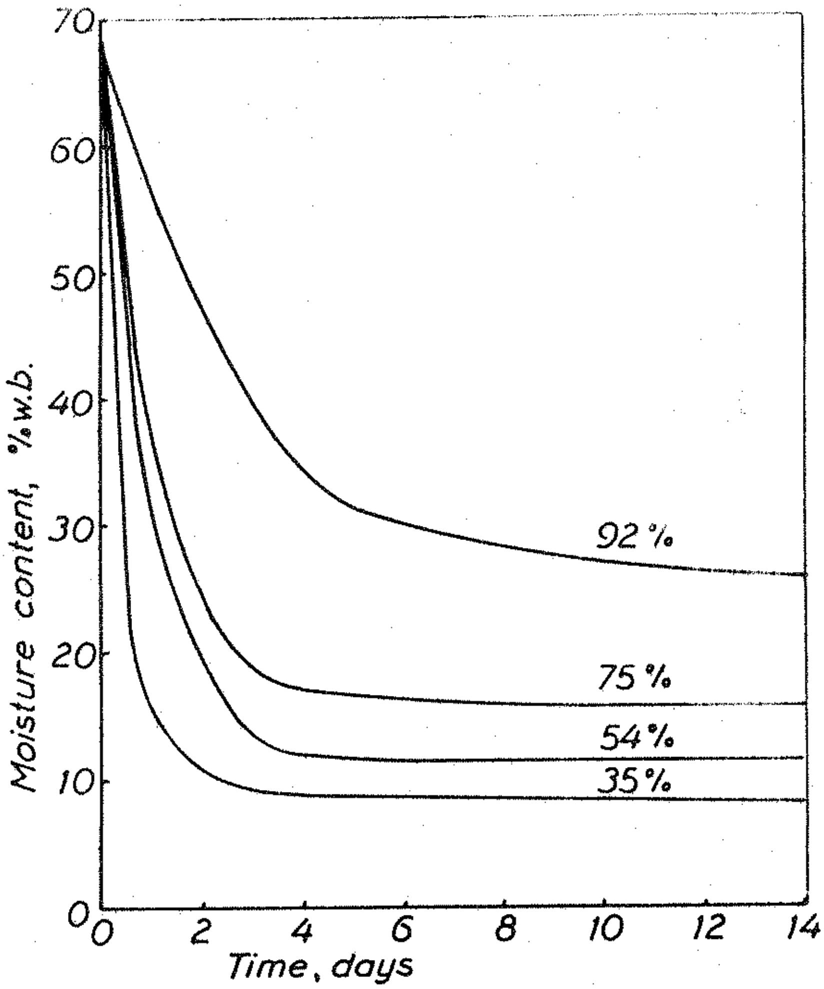

Fig. 25. Moisture content change over time in oat straw, kept in air of different humidities. Harvest 2, 62.6 % initial m.c.

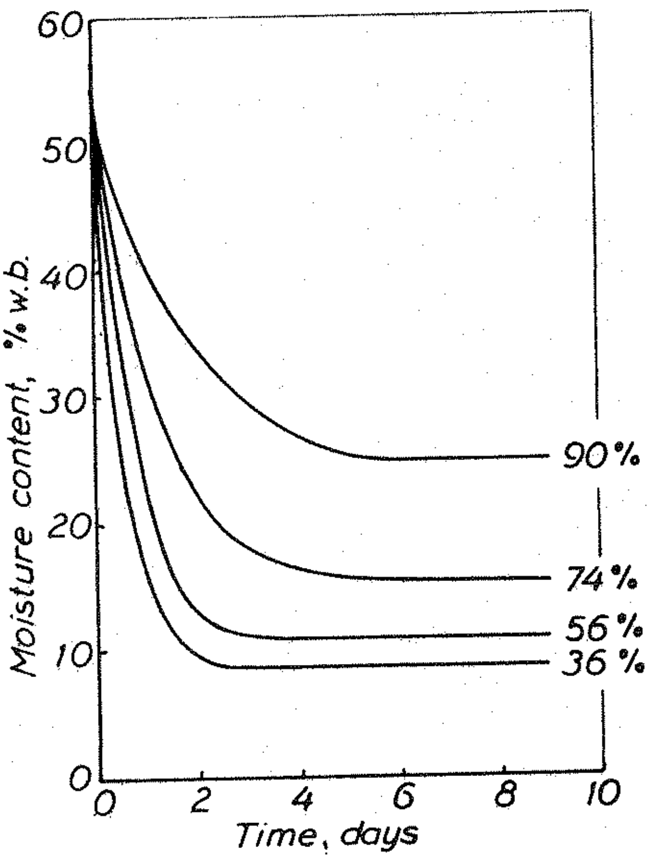

Fig. 26. Moisture content change over time in oat straw, kept in air of different humidities. Harvest 3, 54,0 % initial m.c.

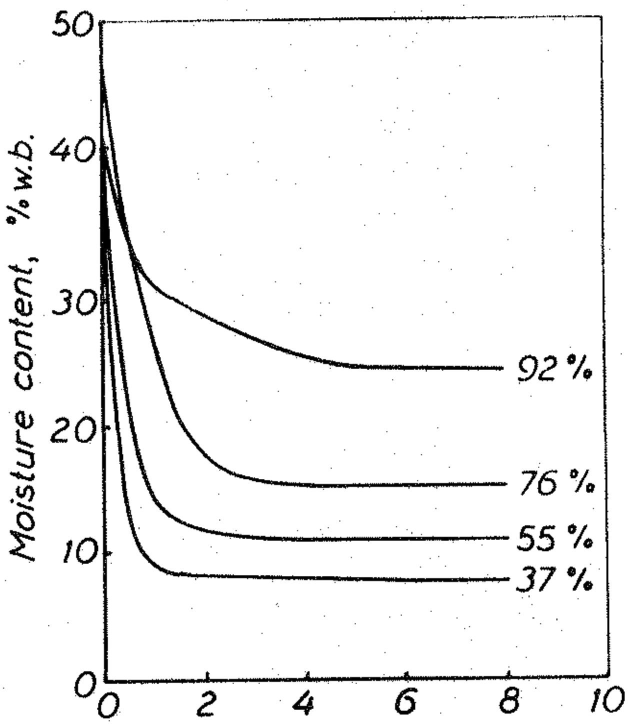

Fig. 27. Moisture content change over time in winter wheat straw, kept in air of different humidities. Harvest 1, 43.4 % initial m.c.

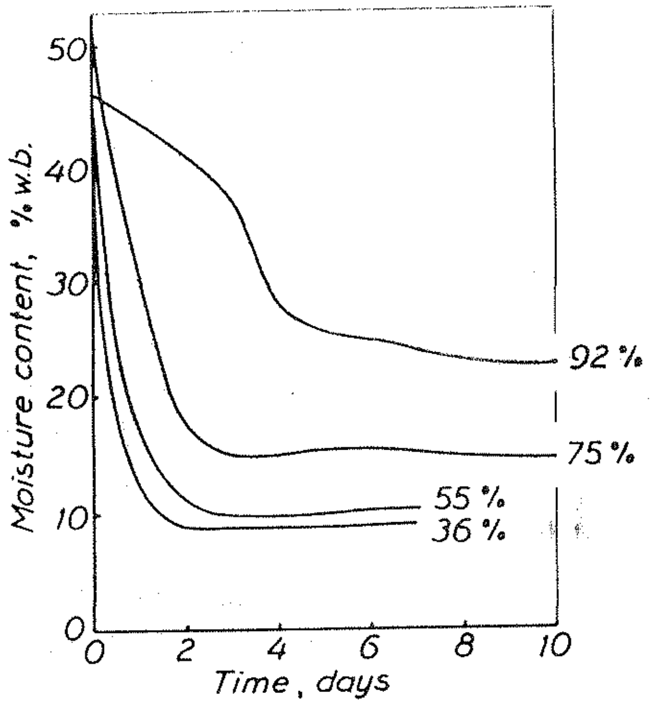

Fig. 22. Moisture content change over time in barley straw, kept in air of different humidities. Harvest 3, 45.2 % initial m.c.

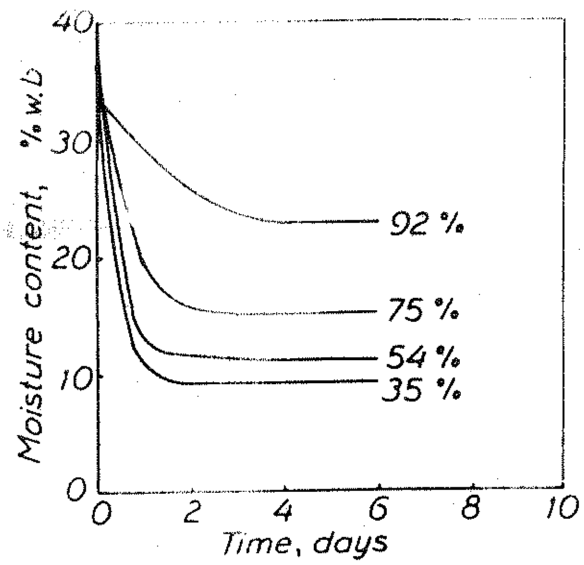

Fig. 23. Moisture content change over time in barley straw, kept in air of different humidities. Harvest 4, 34.5 % initial m.c.

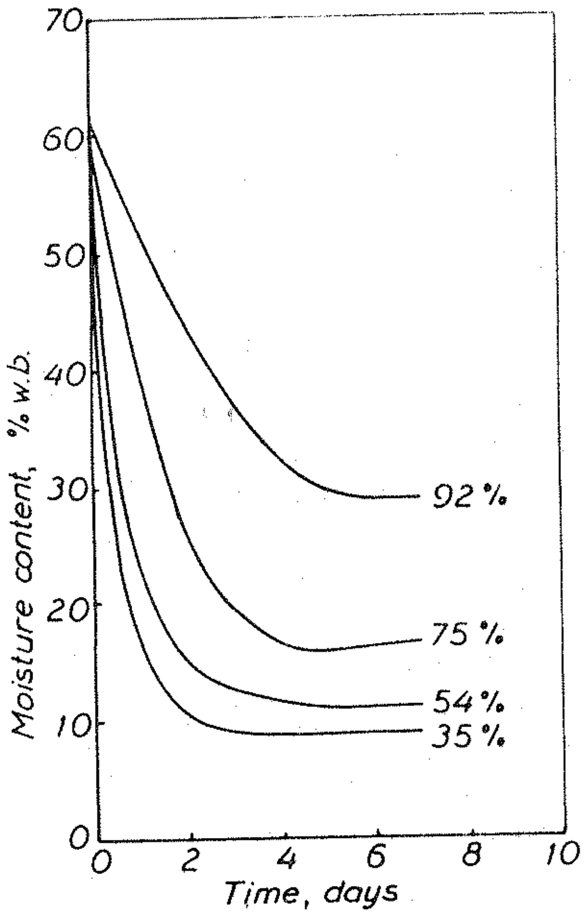

Fig. 24. Moisture content change over time in oat straw, kept in air of different humidities. Harvest 1, 60.5 % initial m.c.

CONCLUSIONS

The most useful results from the EMC investigation, for practical use, are the composite EMC curves for barley, oats, and winter wheat (Fig.'s 13-15). Although the trials provided data for curves at only two temperatures, the temperatures during harvest season typically fall in this range. When using the curves at temperatures outside the 10-20^{o}C range, an approximation of EMC may be possible, since a temperature difference of 10^{o}C only altered the EMC about 2 %. Also, previous studies have shown small variations in EMC between intervals of temperature ranging from 5 to 35^{o}C.

From the results it can be practically stated that at 10^{o}C, barley and wheat straw can be dried to 18 % moisture content using air at about 80 % relative humidity or below, while oat straw requires about 77 %. With 20^{o}C air, barley and wheat require about 83 % relative humidity to reach 18 % moisture content, with oats needing about 79 %.

The results of the EMC trials also showed in another way that oat straw was more difficult to dry than barley or wheat straw. The curves relating moisture content to time (Fig.'s 20-29) showed that, under the same conditions, oat straw would likely have to be dried for a longer period of time than barley or wheat straw.

A desirable moisture content can be reached more rapidly as the relative humidity decreases. The EMC trials showed that 18 % moisture content can be reached with a relatively high relative humidity, but the time to reach this moisture level is greatly reduced when lower relative humidities can be used. However, in practical situations, when straw with very high initial moisture content is dried, it is useful to run the dryer fan, in the beginning, even at humidities of 85-90 % to reduce the risk of heating or moulding.

The results from these trials can be used in many ways, depending on the accuracy needed. The composite EMC curves for straws of barley, oats, and winter wheat are easily and quickly read. Although the results are experimental and the curves are means of different maturity straw, they represent an

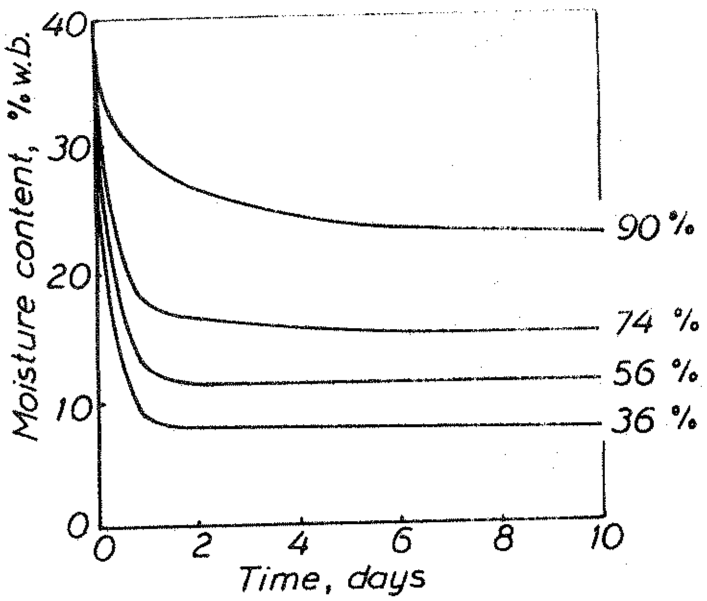

Fig. 28. Moisture content change over time in winter wheat straw, kept in air of different humidities. Harvest 2, 37.1 % initial m.c.

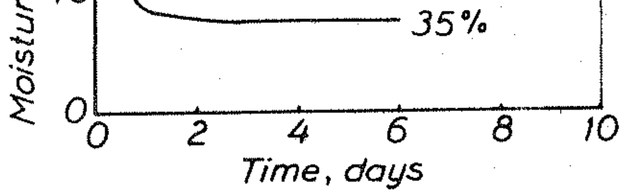

Fig. 29. Moisture content development over time in winter wheat straw, kept in air of different humidities. Harvest 3, 32.1 % initial m.c.

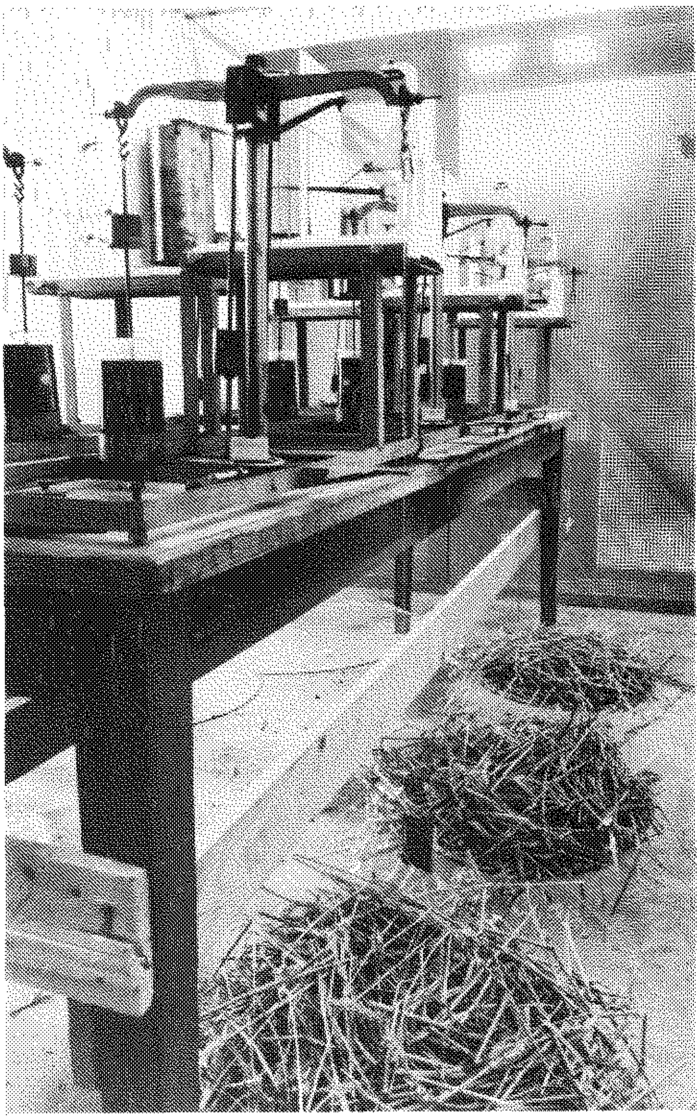

Fig. 30. Straw was placed in baskets, which were hung on the writing balances. Used to simulate field drying under favourable conditions. Photo H. Adefjord.

The experimental conditions allowed the straw to be better exposed to the air than in normal field drying, as more air passed through it than during field drying. Thus, it can be said that the straw was dried when the conditions were optimized. Of course, the straw also was easily remoistened when the relative humidity of the air was high.

The samples were kept on the balances until the instruments were needed for new samples. They were then weighed (to check balance calibration) and the final moisture content was determined.

adequate estimation of when fans should be run in straw drying. These curves are thus useful to the farmer, as well as to handlers of large quantities of straw, like straw-burning plants or briquetting operations.

If more precise drying is desired, the user of the EMC trial results can utilize the results of straw maturity comparisons. The maturity should be viewed, not only by moisture content, but by the age of the crop and the environmental factors affecting rate of maturity.

The results listed in this report are not complete concerning the relationship between EMC and straw maturity, since many natural factors can contribute to maturity.

Further details are also available from the tables in a separate appendix. Tables A1 - A10 give data used to develop Fig.'s 20-29, including the weight and moisture content of each sample every day. This data could be useful in future investigations concerning EMC or dry matter losses. Table A11 gives measured temperature and relative humidity data for the EMC chambers.

SIMULATED FIELD DRYING DURING OPTIMIZED CONDITIONS

The purpose of this part of the investigation was to study changes in moisture content of straw in relation to changes in the properties of passing air. These observations were then to be compared with results from the first part of the investigation, with respect to both relative humidity and temperature.

Materials and method

Two samples of straw, about 200 g each, were taken at each harvest. The initial moisture content was determined from the EMC part of the investigation. The straw samples were placed on baskets (Fig. 30), which were used with "writing balances" (Fig. 31). The writing balances were pre-calibrated from 0 to 200 g before the straw was placed on the baskets. These balances were placed in a closed environment with fans blowing outside air through it. The air passed the balances at about 4 m/s. The temperature and relative humidity of the passing air was recorded by a thermohygrograph.

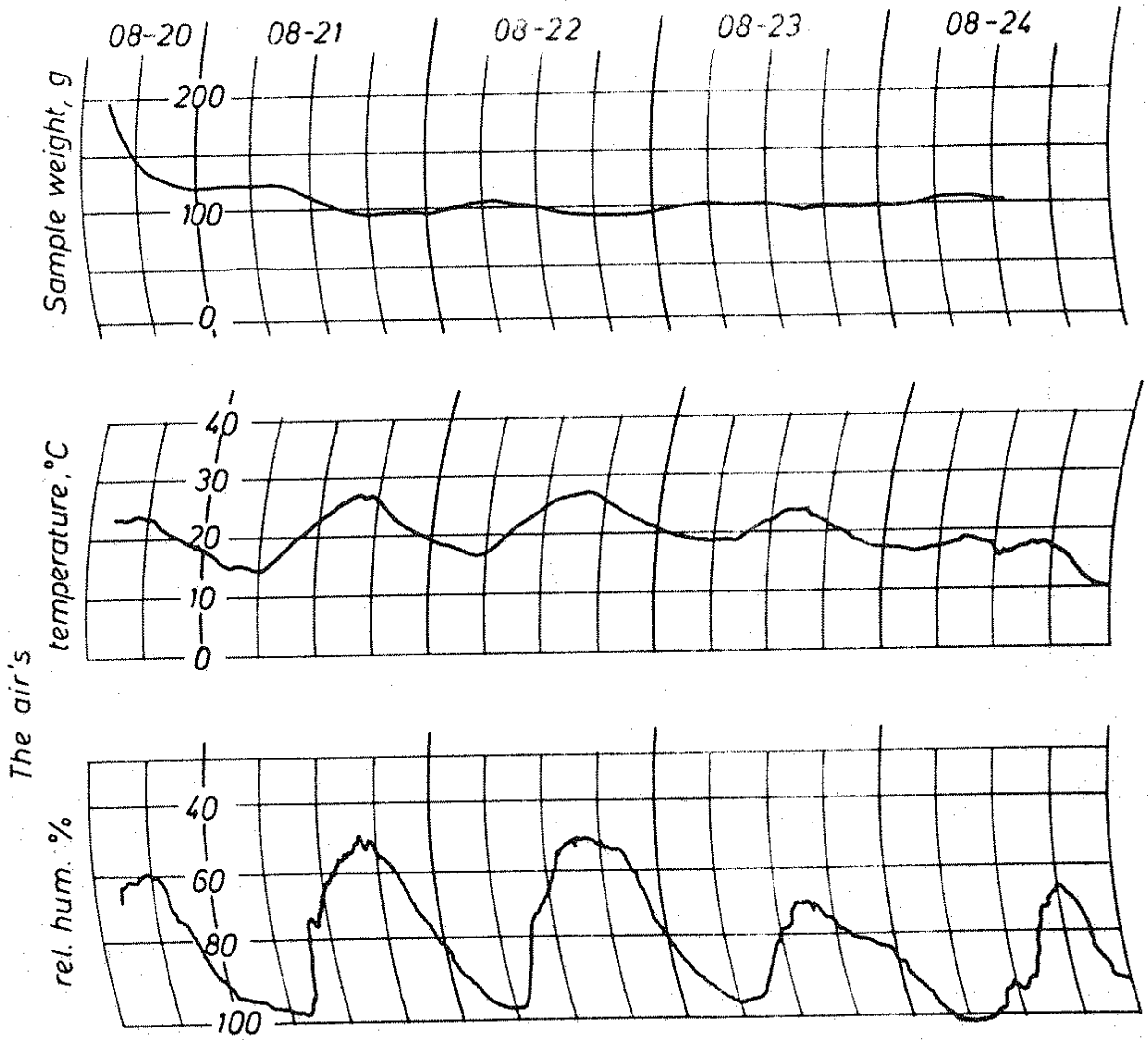

Fig. 32. The upper curve shows weight loss of barley straw over time when ambient air blew past sample on the balance. The sample was from the first harvest at 60.3 % initial m.c. The other curves show the corresponding temperature and relative humidity of the air.

CONCLUSIONS

Comparing the calculated moisture contents with the results from the EMC determinations shows that the straw's moisture content is quick to adjust to changes in the air humidity. This is especially true after some time has passed. For instance, at 22:00 on 22/8 the relative humidity was about 54 %, and the moisture content was calculated as 11.0 %, which is within 0.5 % units of the EMC value. Six hours later, with the relative humidity

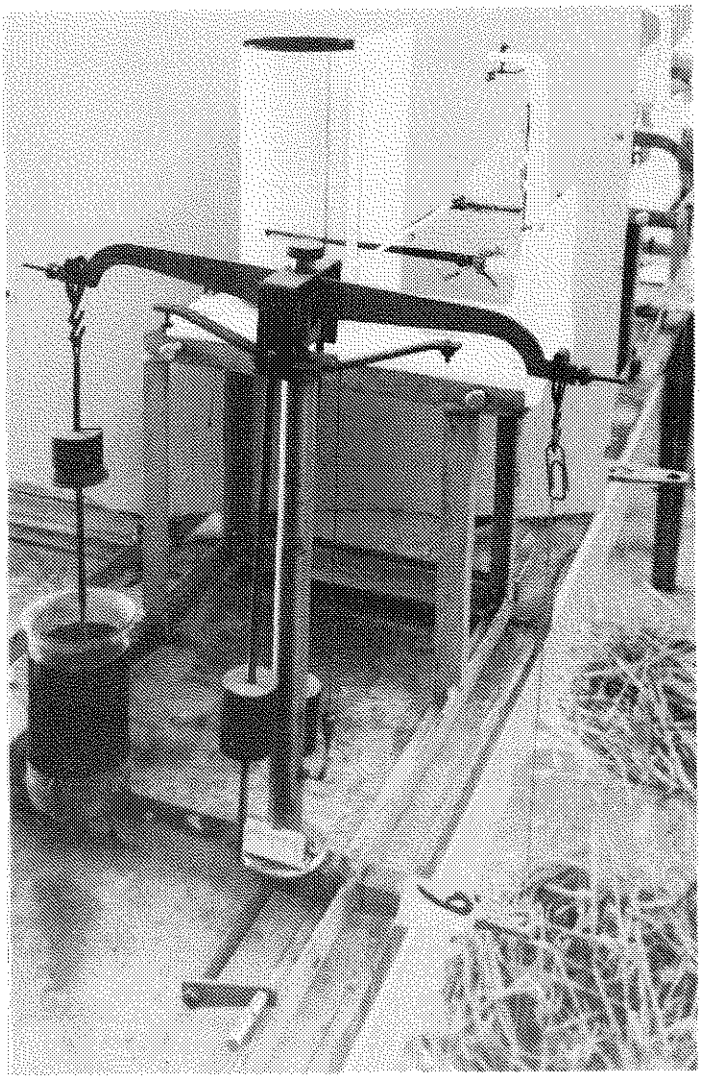

Fig. 31. The writing balance was made by a simple balance and a transformed thermohygrograph. Photo H. Adefjord.

RESULTS

Although time prevented a complete analysis of these trials, the data was collected and some observations made. Fig. 32 shows a typical curve relating the weight loss over time for barley straw and the corresponding temperatures and relative humidities. Using available JTI computer software, points along the weight curve in Fig. 32 were plotted for every two hours, and the corresponding moisture content was calculated. The corresponding temperatures and relative humidities were manually determined for each plotted point, adjusting for the approximate error in the recorded relative humidity (about 8 % units). Table A12 in the appendix shows the results from this example.

The values from the daily weighings were also used to calculate the moisture content day by day. These results showed great differences in drying rates when relative humidity or straw type varied. Trials were also made in simulated field drying during optimal conditions and in normal field drying. These experiments require more analysis before useful results can be stated.

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at about 86 % the moisture content had increased to 16.3 %. This is only about 1 % lower than the EMC for the same 86 % relative humidity.

The other curves will be analyzed at a later date.

FIELD DRYING

Field drying of straw was, to a limited extent, studied during 1982 and 1983 (JTI reports 49 and 54), but more data was sought. In connection to the EMC trials samples were therefore taken, when possible, from the windrow to determine moisture contents.

Initial moisture content after harvest was determined in the EMC part of the investigation. Samples were then taken from the windrow as frequently as possible, usually 3 times a day. The number of samples taken was, however, greatly influenced by an unusually rainy harvest season in 1984. Table A13, appendix, gives a summary of samples taken, with corresponding moisture contents. This data is included only for future use.

SUMMARY

To effectively use a cold air drier it is necessary to know the equilibrium moisture content (EMC) of the material that has to be dried. For that reason an investigation was made to determine the desorption EMC of straw. After the moisture content at harvest was determined, the straw samples were stored in four chambers with constant relative humidities of about 35 %, 55 %, 76 % and 92 %. The samples were weighed every day until the weight was stabilized after which the final moisture content was determined. The trials were made at 20°C and 10°C using samples of barley, oat and winter wheat straw.

The results showed that barley and wheat straw attained an 18 % moisture content with 80 % relative humidity at 10°C, and 83 % at 20°C. Oat straw reguired 77 % relative humidity at 10°C, and 79 % at 20°C.

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