Design curves for drying grains with bentonite

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Watts, K. C., W. K. Bilanski, and D. R. Menzies. 1988. **Design curves for drying grains with bentonite**. Can. Agric. Eng. 30: 237–242. Experimental drying of various grains using previously dried sodium and calcium bentonite clay has indicated a good deal of promise. However, for this method to be practical, one must be able to estimate the final moisture content the grain will reach after being mixed in a given proportion with a clay of a specified initial moisture content. This paper proposes a set of design curves to accomplish this and notes how they are to be used.

INTRODUCTION

Bern et al. (1981), Sturton et al. (1981), Graham et al. (1983) and Watts et al. (1986) have described the drying of various grains by intimately mixing previously-dried bentonite clay with the grain. When compared to simple oil-fired, batch-in-bin grain dryers, the advantages are apparent. The relatively inexpensive clay can be dried using low-cost, low-grade forms of energy (e.g., solar) when the energy is available, such as in the sunny summer months. At harvest time not as much solar energy is available to directly dry the grain, and therefore by using previously dried clay considerable overall system energy savings can be obtained. Because of the intimate mixture of grain and clay, the grain dries uniformly throughout the bin whereas, in a conventional dryer the heating front progresses up from the bottom so that some grain is over-heated while some remains wet for a considerable period of time. The clay in the grain/clay system has the additional property of being sufficiently abrasive to any insects present in the grain to cause them to perish. This protection is effective only as long as the clay and grains are left intimately mixed. Separation of the clay from the grain is accomplished by blowing air through a falling mixture of clay and grain. The clay does not stick to the clay for clay moisture contents below 28% (WB).

To be of practical value, however, a method must be available to quickly and easily make the following determinations: the initial moisture content of the grain and clay; the amount of clay that must be added to the grain to dry it to an acceptable level; by how much the capacity of the existing grain storage bins is reduced due to adding the clay; how long it takes to dry grains with clay; what type of clay should be used.

THEORETICAL CONSIDERATIONS

The process that is being considered consists of a sealed container housing an intimate mixture of grain and clay, each having some known initial equilibrium moisture content before mixing and each having a probably unknown final equilibrium moisture content at some "large" time. The actual time for most grains to come to equilibrium with the clay was found experimentally to be about 30 h.

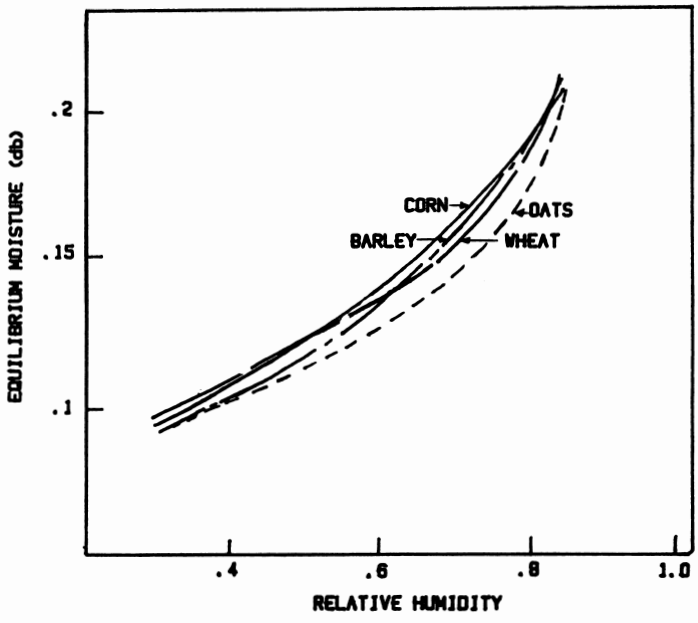


Figure 1. Hygroscopicity curves for grains at 25°C.

The initial moisture content of the grain is a function of the crop maturity, harvesting date, and crop type, while the initial moisture content of the clay is a function of the drying method, etc. Both moisture contents are input parameters. The final moisture contents of each will be a function of their initial moisture contents, the mass ratio of clay to grain, and the hygroscopicity characteristics of the grain and clay.

The hygroscopicity characteristics of grains are quite well defined in the ASAE Standards, both in the form of data and by the Chung or Henderson equations. The equations are made to give the best fit over quite a wide range of temperatures with the result that at some temperatures, the fit is not good. Desiccant drying normally occurs over a small temperature range (15–25°C). Therefore, when the Chung equation did not fit the data at 20 or 25°C to within 0.5% WB on equilibrium moisture (Watts et al. 1987), the raw data at 20 or 25°C was curve fitted to obtain a closer fitting hygroscopicity curve for the grain. The grain hygroscopicity equations used are plotted in Fig. 1.

The hygroscopicity of the clay is more complex due to the large variation in the composition of naturally occurring bentonites, the particle size and absorbed ions. As summarized by Watts et al. (1986), many workers have reported water adsorption curves for sodium- and calcium-based clays. In a confined space, less water can be adsorbed as the clay cannot expand

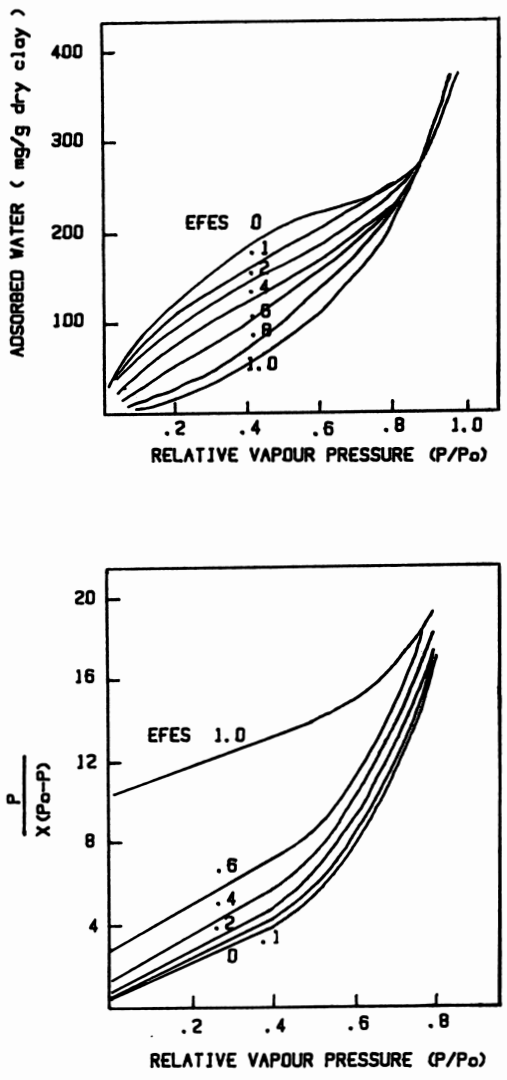


Figure 2.a, Adsorption isotherms on Na^+-Ca^{++} montmorillonite mixtures at various equivalent fractions of exchangeable Na (EFES) at 25°C (Keren and Shainberg 1979). b, BET curves of the adsorption isotherms for the data from Keren and Shainberg (1979). X is the amount of vapor adsorbed at pressure P.

indefinitely; hence, there is a difference in the moisture adsorption isotherm.

To present meaningful design curves for drying grain using clay of poorly defined properties, carefully prepared moisture isotherms for homoionic clays given by Keren and Shainberg (1979) (Fig. 2a) have been used as a standard. The design curves drawn have the purity of the clay as a parameter to allow for deviations from these workers' results. Purity is defined as the factor by which the relative humidity at a given clay moisture content predicted by Keren and Shainberg (1979) must be divided to obtain the actual relative humidity at the equilibrium moisture content. In equation form

$$\text{Purity} = \frac{\text{RH}_{\text{Keren}}}{\text{RH}_{\text{actual}}} \tag{1}$$

These authors found that for relative humidities below 40%, the moisture adsorption of the first monolayer follows the BET (Brunauer, Emmett and Teller) equation (Fig. 2b). However, relative humidities above 40% do occur when drying grains; thus the BET equation does not model the hygroscopicity curves over the whole range of interest of relative humidities. Therefore, for computation, a fourth-order equation was fitted to Keren and Shainberg's (1979) data for different ion compositions, as ion composition has a marked effect on the drying characteristics of a clay.

The value of purity may be found by weighing and measuring the moisture content (DB) of a sample of the clay and the grain to be used; then combining them in one or more sealed jars, and again determining the moisture content of both, separately, after a time lapse of at least 40 h. Using the final moisture content of the grain, the relative humidity at which the grain has reached equilibrium (actual relative humidity) can be determined from Fig. 1. The relative humidity as predicted by Keren and Shainberg is obtained by using the final moisture content of the clay on Fig. 2a for the sodium moisture adsorption curve. It is then possible to calculate the value of purity using Eq. 1. Values of purity for sodium bentonites obtained by workers at the University of Guelph varied between 0.7 and 0.85 as a function of moisture content; these could be used as a first approximation for commercially available Wyoming bentonite.

DESIGN CURVE FORMULATION

A very large number of initial moisture contents are possible for both grain and clay. To simplify the problem for design curves, two conditions are imposed which should exist in practice: (a) the total moisture present in the clay and grain per unit mass (DB) of grain is constant for all times: and (b) for all times, the air surrounding the grain and the clay has identical relative humidities.

From the first condition of conservation of moisture, the following equation may be written for time $t=0$

$$K = M_{IC} \times MR_{CG} + M_{IG} \tag{2}$$

where:
K is the constant total moisture/unit mass of grain (DB decimal), M_{IC} is the initial moisture content of the clay (DB decimal), M_{IG} is the initial moisture content of the grain (DB decimal), MR_{CG} is the mass ratio of the dry clay to the dry grain.

Thus, if the initial moisture contents of the grain and clay are known, it is possible to obtain a value of K, the constant total moisture.

Since conservation of moisture is assumed, Eq. 2 may be rewritten for $t=\infty$ (i.e., when equilibrium has been reached).

$$K = Meq_C \times MR_{CG} + Meq_G \tag{3}$$

Rearranging this equation in terms of the ratio of equilibrium moisture contents yields

$$\frac{Meq_C}{Meq_G} = \frac{\left[\dfrac{K}{Meq_G} - 1\right]}{(MR_{CG})} \tag{4}$$

Thus curves of $\dfrac{Meq_C}{Meq_G}$ vs. Meq_G may be obtained with K and MR_{CG} as parameters. These are the dashed lines on Figs. 3–6.

By imposing the second condition, it is possible to obtain a ratio of the equilibrium moisture contents of clay and grain as a function of relative humidity, where the function is obtained by dividing the hygroscopicity curve for a given clay at a given value of purity by the hygroscopicity curve for grain. Since at equilibrium and at one temperature the moisture content of the grain is a unique function of relative humidity, the equation may be written as

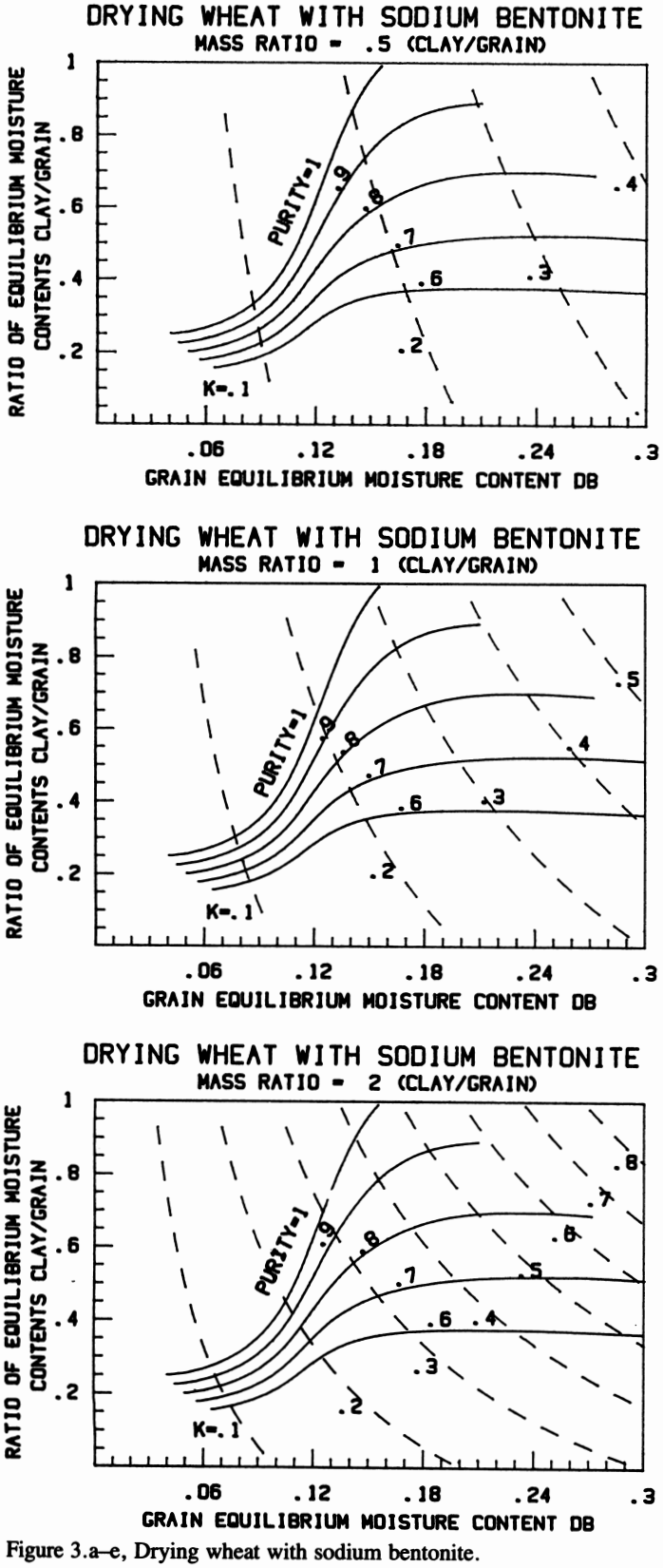


Figure 3.a–e, Drying wheat with sodium bentonite.

$$\frac{Meq_C}{Meq_G} = f(Meq_G) \qquad (5)$$

and the results plotted on the same graphs as Eq. 4. The solution to the final moisture constants of grain and clay will be determined by the intersection of the lines described by Eqs. 4 and 5 for the appropriate parameters. The results for several mass ratios for wheat, corn, oats, and barley are given in Figs. 3–6 for sodium bentonite. Using the same equations, design curves may be produced for any specific clay.

USE OF DESIGN CURVES

A series of figures for each grain have been drawn in which the clay-to-grain mass ratio is the differentiating parameter for each figure. Examination of each series shows that the curves given by Eq. 5 are identical for one series and independent of mass ratio, as expected. This set of curves is unique for one grain and one type of clay. Use of the design curves may be illustrated with the following examples:

Example no. 1.

Problem. A Wyoming bentonite clay (sodium base) having a purity of 0.72 was dried in a solar drier to a moisture content of 2.6% (DB). The moisture content of the corn is 28% (WB) (38.9% DB). The equipment for simultaneously feeding the corn and clay into a common grain bin is set for an approximate mass ratio (WB) of 1:1. The final equilibrium moisture content of the corn must be determined, and whether it will be adequately low to leave the corn and clay together until the corn is to be used.

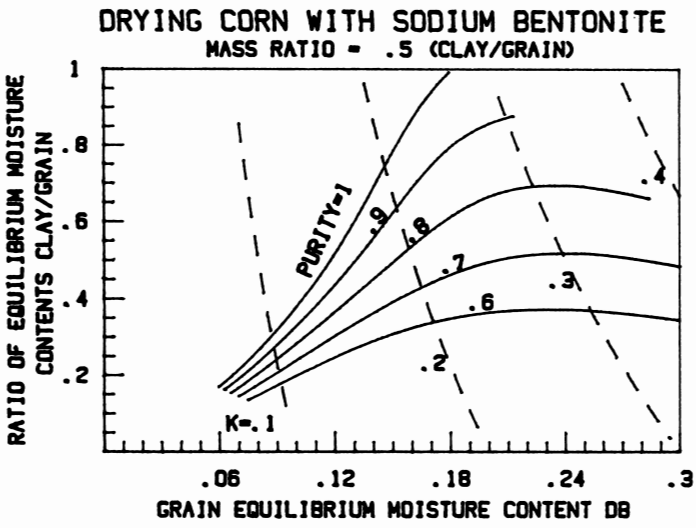
Solution. First, the (WB) mass ratio given (1:1) must be converted to a (DB) mass ratio (1.355:1) before the graphs can be used. Since this value lies between 1 and 2, an average of the results using Fig. 4b,c will yield reasonable results. Approximating the line corresponding to $K = 0.42$ on Fig. 4b reveals that it intersects an estimated line of purity = 0.72 at a point where Meq(grain) = 0.27 (abscissa) and Meq(clay)/Meq(grain) = 0.53 on the ordinate. On Fig. 4c, the Meq(grain) = 0.205 and Meq(clay)/Meq(grain) = 0.53. Thus, the corn will equilibrate at a moisture content of $0.27 - (1.355-1)/(2-1) \times (0.27-0.205) = 24.7\%$ (DB) (19.8% WB), and the clay at a value of [Meq(clay)/Meq(grain)] × Meq(grain) = 13.1% DB (11.6% WB). Thus, the moisture content of this corn is insufficiently low for safe storage; hence, a higher mass ratio of clay to corn should be used initially, or the corn and clay mixture used should be separated using a blower and the 24.7% MC corn be recombined with dry clay for storage.

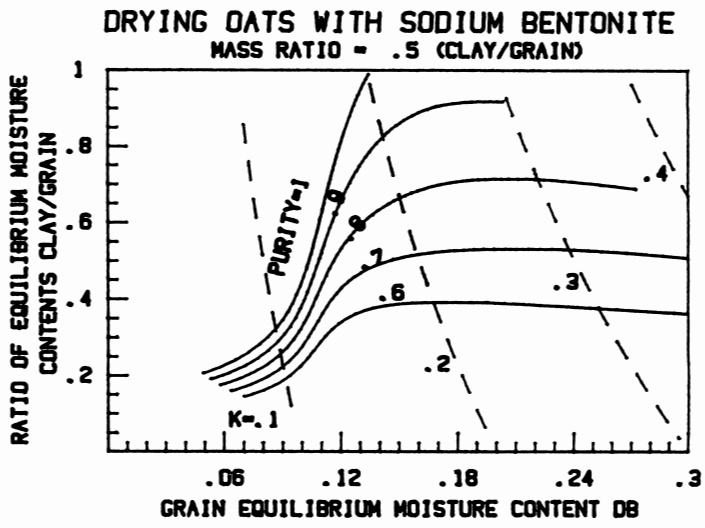
Example no. 2

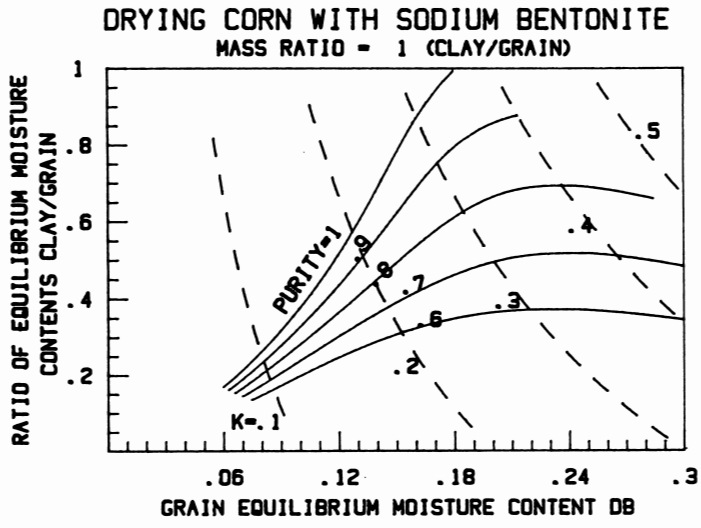
To determine the mass ratio of clay to grain for some desired final grain moisture content, the Figs. 3–6 are useful as illustrated by the following example:

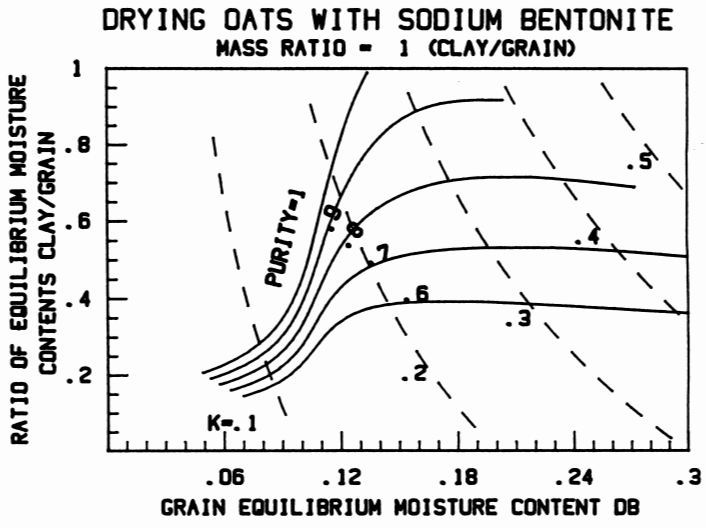
Problem. Wheat at 22% (WB) must be reduced to 15% moisture (WB) for optimal storage. Using sodium bentonite of 0.80 purity at 6% (WB) moisture, the amount of clay needed to achieve the above moisture reduction in the wheat must be determined.

Solution. Converting the WB values to DB yields $M_{IG} = 0.282$, $M_{IC} = 0.064$ and $Meq_G = 0.176$. The final equilibrium grain moisture value (0.176) can be entered onto Fig. 3a–c to intersect the solid lines at an approximate purity value of 0.80. This will yield a different K value on each figure, depending on the mass ratio; however, the ordinate which is the ratio of equilibrium moistures remains the same on each graph. Plotting K (total moisture content) vs. mass ratio on a graph yields a straight line (Fig. 7).









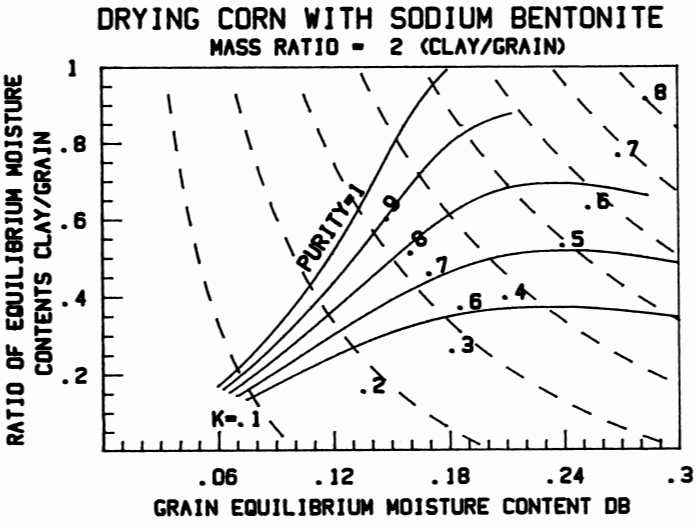


Figure 4.a–e, Drying corn with sodium bentonite.

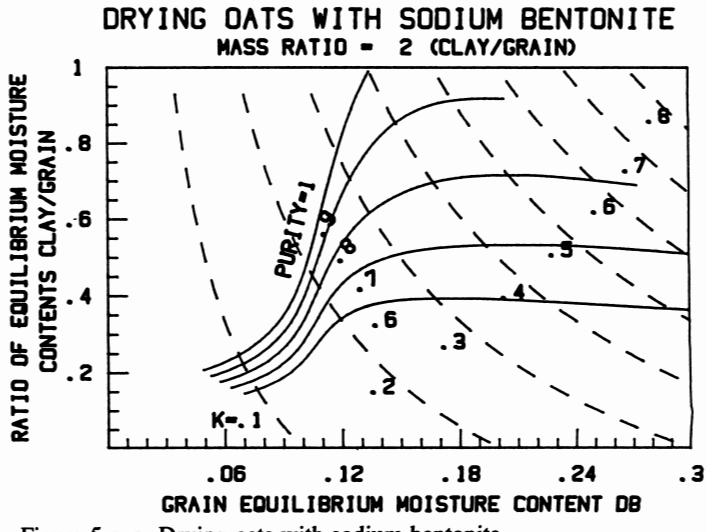
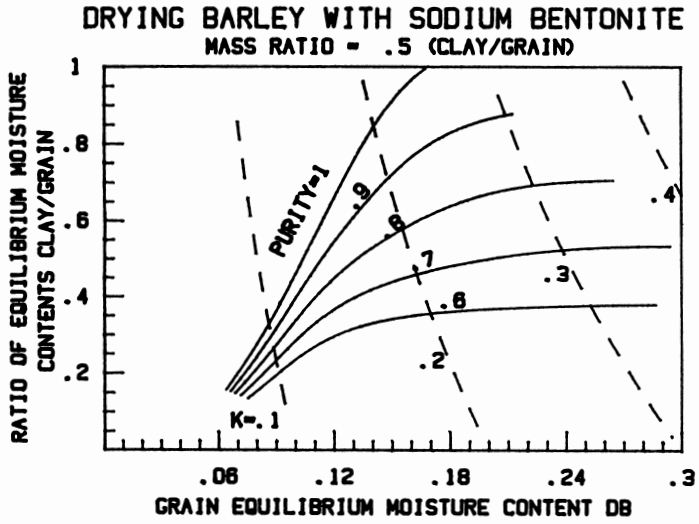


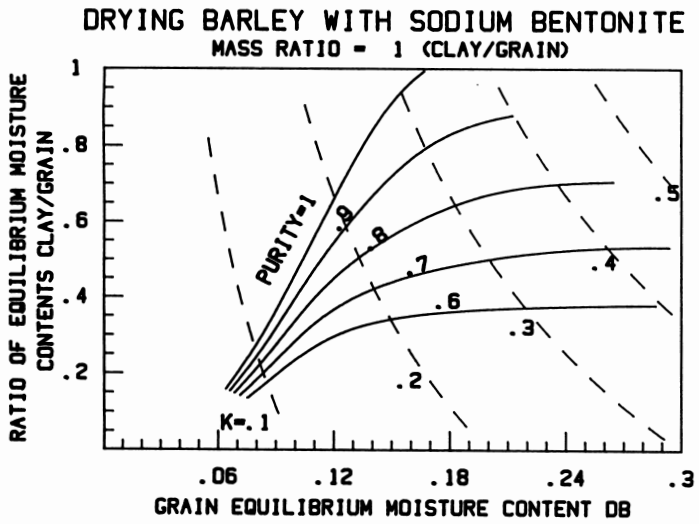
Figure 5.a–e, Drying oats with sodium bentonite.

Another straight line of K vs. MR_{CG} can be obtained using the initial moisture contents (DB) of wheat and clay with mass ratio as a variable (Eq. 2) and plotting these on the same graph. The desired mass ratio is shown as the intersection of the two lines (in this example, 2.05).

OTHER CONSIDERATIONS

The accuracy of any calculation or design procedure is always of great interest. The authors checked all their data with the above method and arrived at the predicted grain equilibrium moisture content to within 1% (DB) of the actual moisture content. The greatest source of error lies in the estimation of the





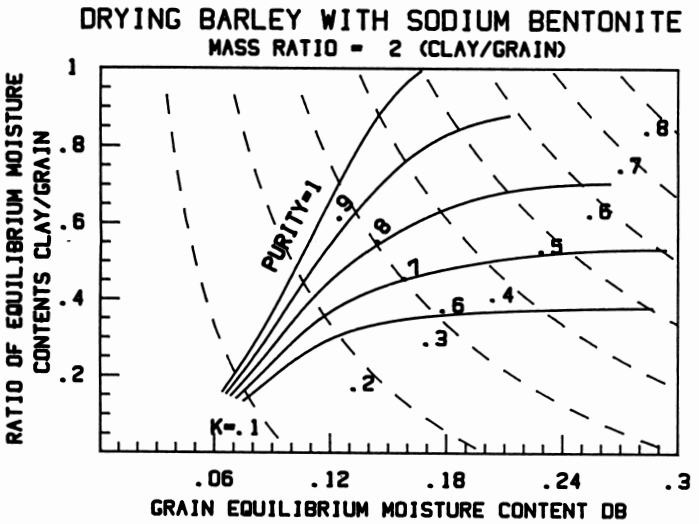


Figure 6.a–e, Drying barley with sodium bentonite.

hygroscopic properties of the clay. The one-point determination of the purity noted above is most accurate if it is determined for the moisture content range which the clay will experience. The error on final grain moisture for a change in purity from 0.7 to 0.8 can be seen to be of the order of magnitude of ½% for K = 0.2 and a mass ratio of 1 for corn (Fig. 4b). As the

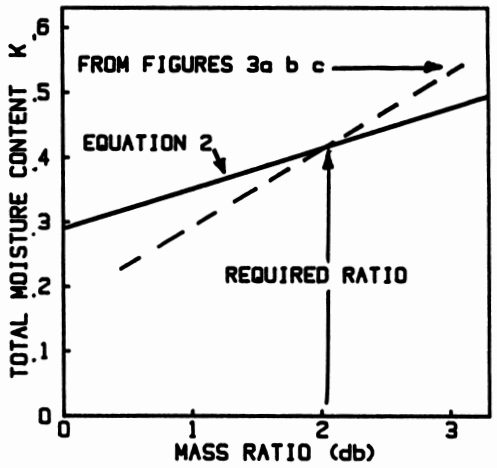


Figure 7. Example of determination of mass ratio of clay to grain.

clay content increases (e.g., to a mass ratio of 5 clay/grain) and K increases to 0.8, the error on final corn moisture increases to about one per cent. Results are similar for other grains.

EFFECT OF CLAY ON STORAGE REQUIREMENTS

No grains completely fill all voids; hence, there is space available for the very much smaller clay particles to fill. The increase in storage capacity required as a function of mass ratio can be computed from information on the void fraction (bulk density/particle density) of the grain and the ratio of the bulk densities of the clay and grain. Figure 8 shows the results. It is thus apparent that no increase in storage capacity is needed for the actual storage of clay below a certain mass ratio for each grain. However, from a logistics point of view, one spare container is required to hold the clay in order to effect mixing the clay and grain by the simultaneous augering of the two components into another bin as the grain is put into storage.

Above the mass ratio at which extra storage is required, the increase in storage, per unit mass of grain, varies with the ratio of bulk density of grain to clay. Considerable increase is noted for wheat and corn at a mass ratio of 2, for example.

USES OF CURVES FOR CALCIUM BENTONITE

Although it is possible to relate purity to Keren and Shainberg's data for calcium-based clays and then produce similar design curves for calcium bentonite, it is also valid to use the design curves presented in this paper and refer the purity number of

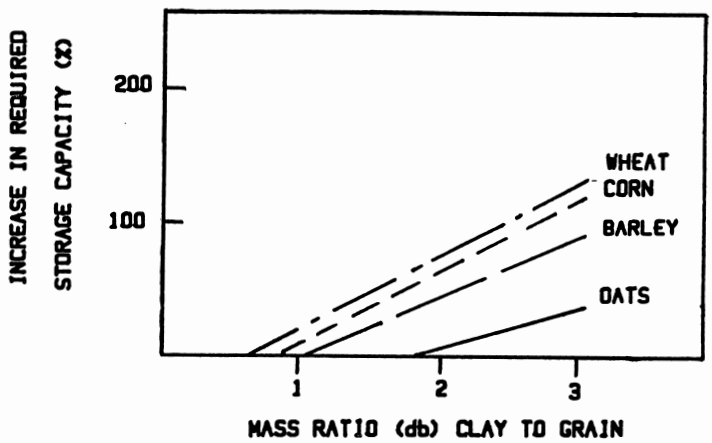


Figure 8. Increase in requirements of storage capacity.

the calcium clay to the sodium-based standard. The only precaution that must be followed is to obtain values of purity over the whole range of moisture contents of interest, since there is likely to be considerably more variation in purity with moisture content than with a sodium-based clay. Therefore a purity line would have to be plotted for the clay in question derived from the experimental hydroscopicity data obtained on the clay.

CONCLUSIONS

(1) Design curves, as presented, may be used to determine the final moisture content that an intimate mixture of clay and grain would reach when combined at a given mass ratio and purity of clay. Considerable advantage is seen in using a very low clay moisture content.

(2) The best experimental method to determine the purity of clay is obtained by mixing samples of clay and grain for which the weight and initial and final moisture contents are known (Watts et al. 1987).

(3) No increase in mass storage capacity is required at low mass ratios, but a significant increase is noted at higher ratios of clay to grain.

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