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FINENESS PARAMETERS OF CROP GRINDS STUDY ON HAMMER MILL AND GRINDING FORAGE AND ENERGY CROPS

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Abstract: From the data base of a many-year hammer-mill test series on grinding different grains and other vegetable materials (energetic biomass included) in different conditions, data points of the conjugate particle-size and calculated specific surface-area values were plotted in. The close fit of the curves indicates an apparently simple characteristic relationship (model law) between the two fineness parameters of grinds – the specific surface area vs. nominal particle. The gained regression function is a simple general hyperbola – the “fineness characteristic curve”.

INTRODUCTION

In many modern, high production plants where the equipment runs at least two shifts per day, the cost of energy during one year can easily exceed the cost of a new hammer mill. In other words, the energy to operate a hammer mill (or roller mill) during its normal expected life will be 10 to 20 times more expensive that the machine cost alone.

Similarly, the *energy requirement* and the *cost of grinding exponentially increase with the fineness* of the finished product (grinds or grits) (Figure 1).

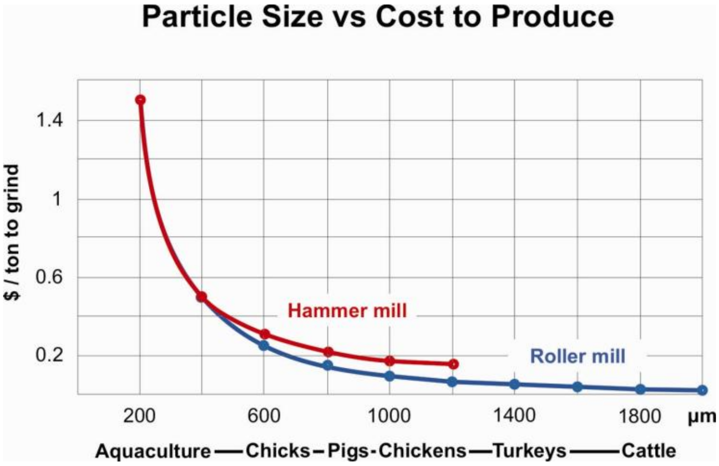


Figure 1. Cost of production as a function of grits fineness (mean particle size) [2]
with typical fineness ranges for different farm animals and aquaculture

1. DETERMINING AND EXPRESSING OF GRITS FINENESS

Determining and expressing fineness of grind has been the subject of study as long as feed ingredients have been prepared. While appearances or feel may allow an operator to control a process, subjective evaluation is inaccurate at best and makes objective measurement and control virtually impossible. Descriptive terms such as coarse, medium and fine are simply not adequate. Describing the process or equipment is also subject to wide differences in terms of finished particle size(s) produced.

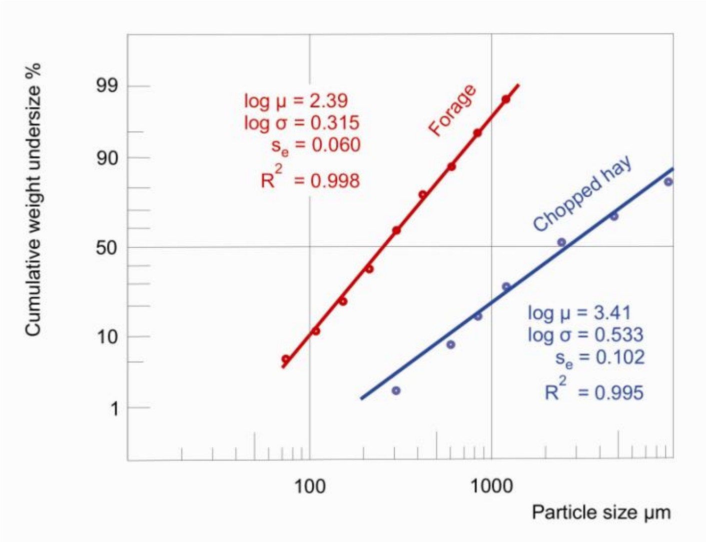
Factors such as moisture content of the grain, condition of the hammers and/or screens (hammer mill) or the condition of the corrugations (roller mills) can produce widely varying results.

In addition, the quality of the grain or other materials being processed can have a dramatic impact on the fineness and quality of the finished ground products.

The best measurement of finished particle sizing will be some form of *sieve analysis*, expressed in terms of mean particle size or percentage (ranges) on or passing various test sieves. A complete sieve analysis will not only describe the average particle size but will also indicate peculiarities in the distribution, such as excessive levels of fine or coarse particles, etc. Typical descriptions that lend themselves to objective measurement and control might be "corn ground to 750 microns" or "75% ≤ 14 meshes".

The widespread methods of determining the fineness parameters i.e. particle size and (specific) surface area of grits give well reproducible results, however, those (apart from the rare exceptions) cannot generally be transformed into the other analytic processes. As to the measurement error, according to Heywood, the results of sieving analysis scatter in the range of ± 17 % as compared to the average value at a 95-% confidence level, in all particle-size ranges.

To express the fineness of ground feed materials, the *log-normal approach* has been approved as a standard for grains, concentrate size distribution, amongst others all over the world, by the American Society of Agricultural Engineers as well (*1969*). An interesting and important extension of this representation was when the method had been approved for use and describing such extreme materials as forage particles (*chopped or pelleted grass hay*), cow rumen and faecal materials as well (Figure 2).



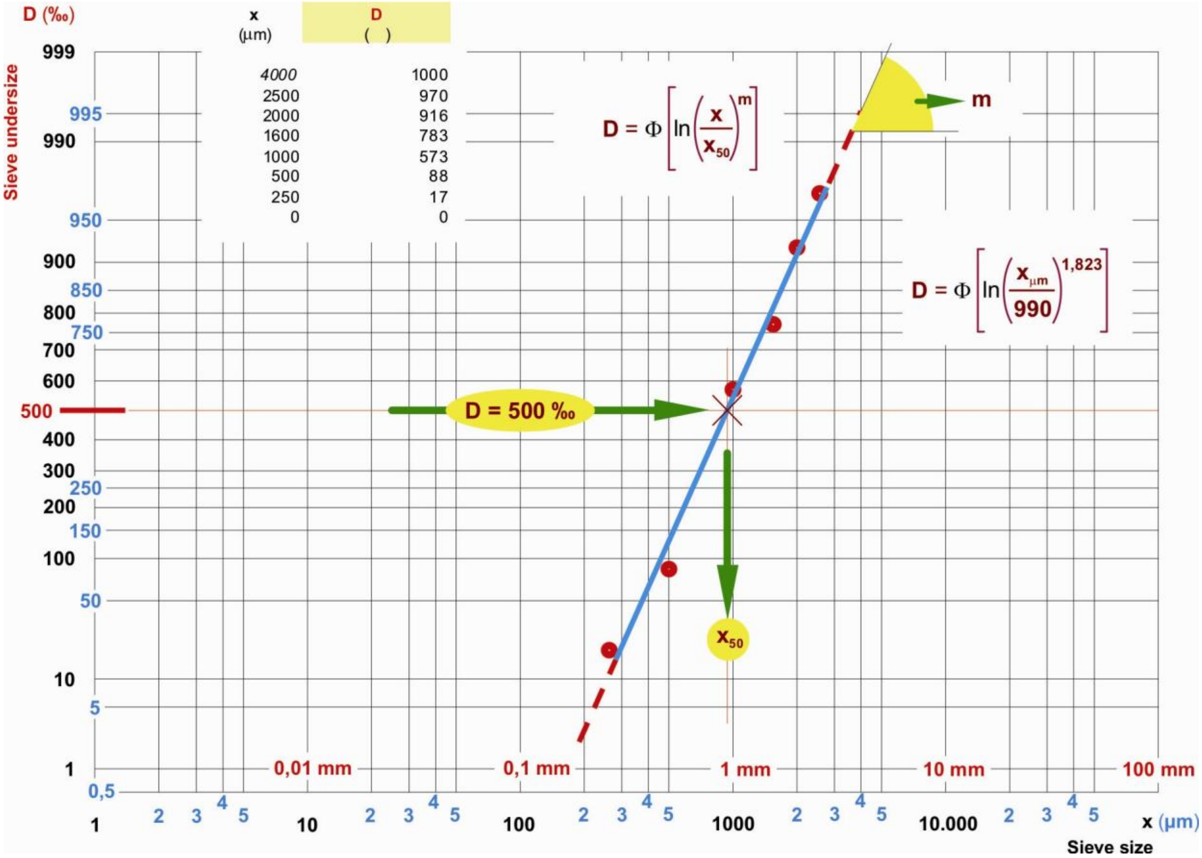
Waldo et al. 1971

Figure 2. Log-normal probability plots of forage sieve data on the left and a randomly selected sieving of chopped hay on the right

Regression parameters: log μ – log_{10} mean; log σ – log_{10} standard deviation; s_e – pooled residual standard deviation for sample set

For different kinds of forage materials, a size class, as characterized by a given sieve size interval, does not necessarily mean the same thing with respect to actual size (volume, surface area, or weight) of individual particles. This problem can only be overcome by particle characterization methods other than simple sieving – such methods would have to separate by shape (and maybe density) as well as by size.

This, however, is a question independent of whether the log-normal distribution characterizes simple sieving results. It can be stated: *if simple sieving* of feed materials or forages is *acceptable*, then the work here reported *justifies* use of the *log-normal description* (Figure 3). The particle-size distribution curve “straightens” when sieve data plotted on the logarithmic Gaussian paper (diagram net) and the regression becomes simplified to fitting a line (linear regression).

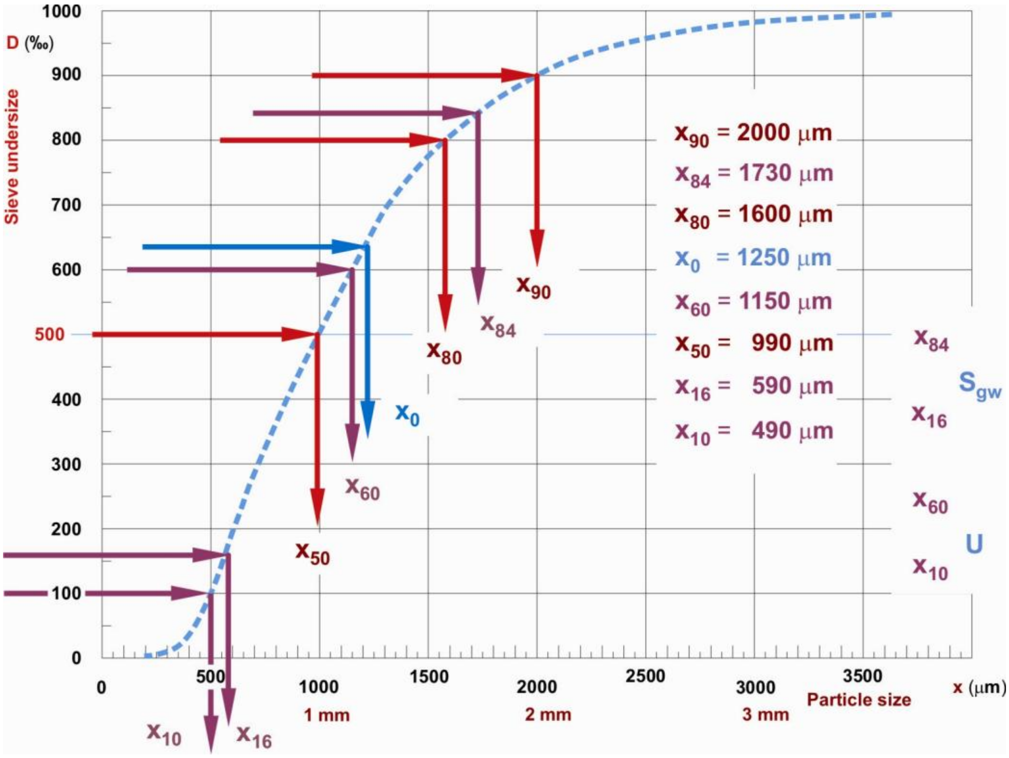


Fogarasi 2009

Figure 3. The general lognormal representation of particle size distribution of grinds plotted on logarithmic probability (Gaussian) paper *(an arbitrarily selected sample)*
x_{50} – particle size to D = 50 % (here 500 ‰); m – slope of the regression line in the diagram net

The known expressing methods of fineness of ground feed materials use very different (so-called nominal or characteristic) particle sizes. These all can be determined from a well constructed distribution diagram and it is a very useful tool when different (especially old or conservative) data bases must be interpreted, analysed or compared (Figure 4). The characteristic particle sizes scribed in the linear-scale particle-size distribution diagram shows quite a crowded picture.

Without knowing the full distribution (or at least the model law and deviation parameter), neither the specific surface area of grinds can be determined nor the nominal particle sizes can be transformed into each other.



Fogarasi 1996

Figure 4. Particle size distribution of grinds – different nominal particle size values

E.g. x_{90} – particle size to D = 90 % (here 900 ‰) etc.; x_{90}, x_{80} – parameters from earlier industrial or scientific tests; x_0 – nominal particle size of RR(S)B model (DIN standard); x_{50} – median particle size by mass (e.g. Hungarian, ISO, ASAE standards); x_{60}, x_{10} – auxiliary parameters for calculating the non-uniformity factor U by Hungarian standard; x_{84}, x_{16} – auxiliary parameters for calculating the geometric standard deviation of particle size S_{gw} by ASAE; m – slope of the regression line in the diagram net

2. RELATIONSHIP BETWEEN SPECIFIC SURFACE AREA AND PARTICLE-SIZE DISTRIBUTION

Theoretically, a measured and expressed particle-size distribution can be converted into the parameter of specific surface area of the particles but, contrarily, there is no way to reconvert the already known specific surface area value of a ground material into its particle sizes (especially its particle-size distribution). According to Kihlstedt's hypothesis, the Bond's nominal particle size ***Z*** – an earlier used industrial fineness index, d_{80} or x_{80}; the size of the sieve which the 80 % of particles falls through – is in a direct relationship with the specific surface area (Figure 5):

$$A_{\text{volspec}} \sqrt{d_{80}} \cong \text{const} \tag{1}$$

where: $A_{\text{vol spec}}$ is volumetric specific surface area (cm^2/cm^3)
d_{80} is Bond's index *Z* – the nominal particle size at 80 % cumulative mass of undersize

Kihlstedt's relationship is a general hyperbolic function, however in his calculations, the constant value of about 750 altered according to the sieve sizes but it proved statistically correct in the domain of usual sieve analysis between 75 and 50,000 μm. Anyway, the hypothesis is based on the traditional Gaudin-Andreyev-Schumann logarithmic distribution model which is a quite good approach (linear when plotted on a log-log paper) up to D = 80 to 90% undersize values.

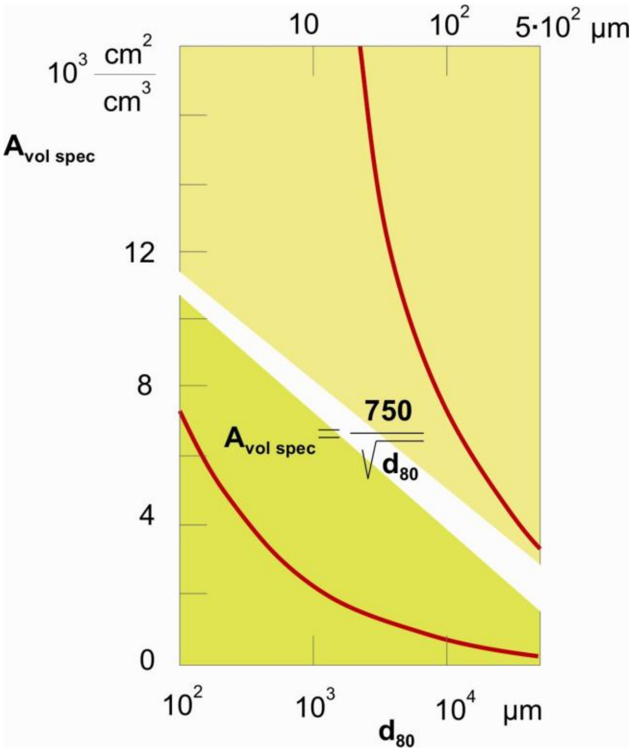


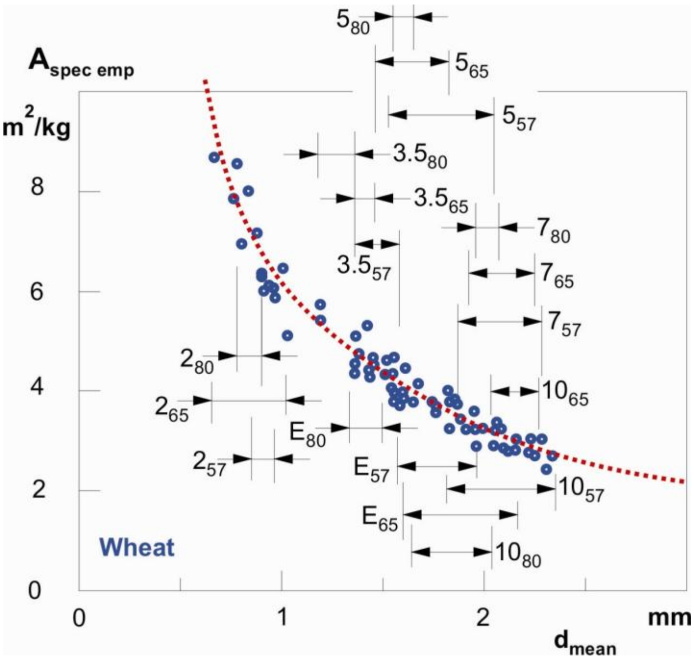
***Figure 5. Kihlstedt's relationship: the volumetric specific surface area of the ground material as a function of the nominal particle size d_{80}** (originally **Z**)*
An empirical curve fitted on a multi-element measured-computed point set of quite different industrial (mineral) materials, scattering in a wide range

The specific surface area of the ground material A_{spec} plays a significant role in the different comminution-energetic theories and investigations; the input grinding (crushing) work is in a certain proportion to the newly produced particle-surface area. In fact, the value of the specific surface area of a granular (powder) bulk is a fineness parameter – and, in addition, it is only a single figure of characterizing the particle fineness, however, not a simply "sensible or tactile" property in comparison with the particle size.

The (specific) particle-surface area data directly measured by one of the introduced methods are not reliable at all; the different techniques yield very different values even of the same sample. The difference could be of two times in order of magnitude so it is expedient to use the calculated surface area. However, due to the simplifications, the computed parameter is not the real surface area of particles but a number as a good surface area character.

From the data base of a many-year hammer-mill test series on grinding different grains and other vegetable materials in different conditions, using Kihlstedt's investigation as a model, the data points of the conjugate particle-size and calculated specific surface-area values were plotted in diagrams and regression functions (curves) were fitted on the "measured" points (Figure 6). [1] The close fit of the curves is clearly shown in the figures, indicating an apparently simple characteristic relationship (model law) between two fineness parameters of the samples of grinds – the specific surface area vs. nominal particle. Here the selected parameters are the ordinary average (mean) particle size d_{mean} (or x_{mean}) and the ordinary (so-called "empirical") specific surface area ($A_{spec\ emp}$, assuming that the particles of grinds are cubic); both can directly be calculated from the data sheet of sieving analysis, however, with full knowledge of the size distribution, the calculation is refined and more accurate. The diagrams plotted with other nominal particle sizes e.g. x_0

or x_{50} (d_{50}) and specific surface areas A_{spec} computed by arbitrarily chosen techniques (e.g. according to the RR(S)B model or ASAE standard) result in very similar function type.



Fogarasi 1990

Figure 6. Storage-dry wheat grits – Empirical specific surface area $A_{spec\ emp}$ vs. average particle size d_{mean} by mass

Conventional hammer-mill screens: 2, 3.5, 5, 7 and 10 – diameters of screen aperture (punched round holes) in mm; Screen of expanded steel plate E – similar to the conventional 5-mm screen as to its size; Lower indices – 57, 65 and 80 m/s measured hammer-tip (peripheral) speed

In this case, the regression curve is the simplest general hyperbola; for *wheat* samples its equation is

$$\overline{A}_{specemp} = \frac{7.80}{d_{mean}} \qquad (m^2/kg) \qquad (2)$$

where: d_{mean} is the ordinary average particle size (otherwise x_{mean} or x_{ave}), mm

Very similar regression functions were gained in the case of barley and maize kernels ground by the test hammer mill with 12 hammers (Figures 7 and 8).

It is worth mentioning that, according to independent measurements grinding barley by a similar hammer mill with 24 hammers (*Bölöni 1989*), this function is

$$\overline{A}_{specemp} = \frac{8.15}{d_{mean}} \qquad (m^2/kg) \qquad (3)$$

where: d_{mean} is the empirical average particle size, mm

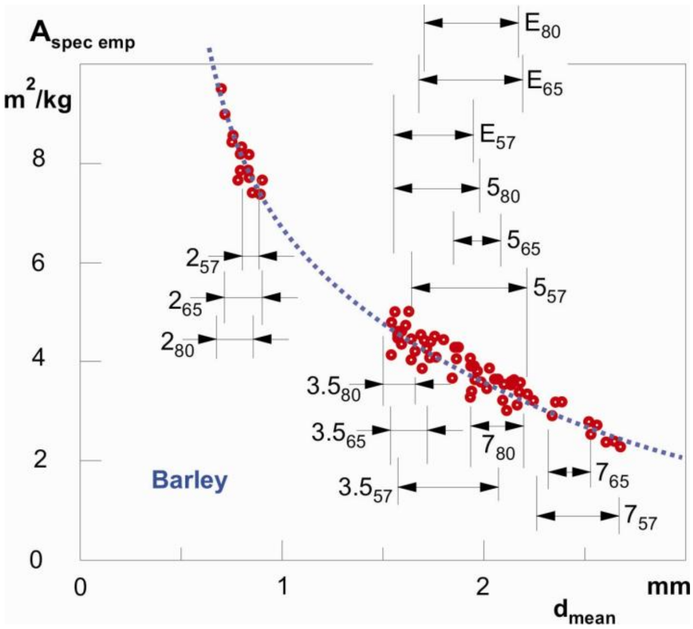
If the above equations are transformed to the solid-matter density of 1000 kg/m^3 (or the volume base), the following formulae are gained:

$$\overline{A}'_{specemp} = \frac{10.64}{d_{mean}} \qquad (m^2/kg) \qquad \text{for wheat (12-hammer mill)} \qquad (4)$$

$$\overline{A}'_{specemp} = \frac{10.61}{d_{mean}} \quad (m^2/kg) \qquad \text{for barley (24-hammer mill)} \tag{5}$$

where the body-density of kernels ρ_{solid} = 1000 kg/m^3 – an imaginary density value

The shape of these formulae requires an extraordinary attention.



Fogarasi 1996

Figure 7. Storage-dry barley grits – "Empirical" specific surface area $A_{spec\ emp}$ vs. average particle size d_{mean} by mass

Definition of lettering: See Figure 6

This essential relationship can be considered as the fineness characteristic curve of an actual material to be ground in a hammer mill which is invariant independently of the operating parameters such as mill screen size, peripheral speed, and mass flow.

The above correlations can be proved in an analytical way as well. Apart from the detailed discussion, the ASAE standard process is taken here for demonstration as it follows.

The equation for estimating the total surface area of particles in a sample charge is:

$$A_{st} = \frac{\beta_s W_t}{\beta_v \rho} \exp\left(4.5\sigma_{ln}^2 - \ln \mu_{gw}\right) \tag{6}$$

where:

A_{st} is estimated total surface area of a charge (sample), cm^2
β_s is shape factor for calculating surface area of particles. Cubical, β_s = 6; Spherical, β_s = π
β_v is shape factor for calculating volume of particles. Cubical, β_v = 1; Spherical, β_v = π/6
ρ is particle density of the material, g/cm^3
σ_{ln} is log-normal geometric standard deviation of parent population by mass in natural logarithm, use S_{ln} as an estimate
μ_{gw} is geometric mean particle diameter of parent population by mass, cm, use d_{gw} as an estimate
W_t is mass of a charge (sample), g

If the constant properties are included in a single parameter C_{ASAE}, the above equation, substituting the measured-calculated variables S_{ln} and d_{gw} (or d_{50}) for σ_{ln} and μ_{gw}, respectively, can be written down with the following formula:

$$A_{st} = C_{ASAE} \frac{e^{S_{ln}^2}}{d_{gw}} \qquad (cm^2) \qquad (7)$$

During an earlier research (*Fogarasi et al. 1990*) it was derived that the deviation-property of the particle-size distribution of hammer mill products (in the forms of standard deviation, n, U, S_{gw} or S_{log} as well as m) behaves as a probability variable itself, and has an expectable value (or average value) in fixed conditions – in the case of the same material and the same mill. With this, the expectable value of S_{ln} can be substituted in the numerator of the above fraction:

$$A_{st} = C_{ASAE} \frac{e^{\overline{S}_{ln}^2}}{d_{gw}} \qquad (cm^2) \qquad (8)$$

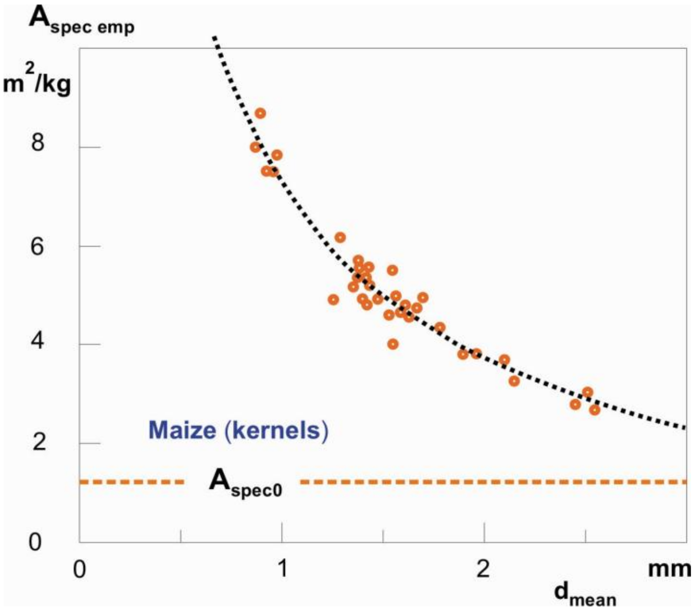
Accordingly, after determining the expectable value of S_{log} or S_{gw} (more exactly its mean value calculated from a quite large series of ground samples) the equation can be written down as –

$$A_{st} = \frac{C'\left(\overline{S}_{gw}\right)}{d_{gw}} \qquad (cm^2) \qquad (10)$$

And this is a similitude of the above simple hyperbola – a material grinding and machine characteristic function or otherwise “fineness characteristic curve” which can be determined by tests for each hammer mills (probably for other mill types as well) and materials to be ground. Knowing the actual characteristic curve, the grinding calculations and the analysis of the mill operation can significantly be simplified. In a certain sense, the constant of the characteristic function can be considered as a special grinding material property.

3. SPECIFIC SURFACE AREA OF WHOLE GRAINS

When grinding, one of the most important character of the grinding performance is the produced new surface area (so-called surface-area increase) which is the difference between the surface area of the fine grits particles and that of the input material (Figure 8). In the actual cases, the input material frequently is fed in the form of whole grains. The behaviour of the grains is different from the comminution of the already crushed particles and the acceptable determination of its specific surface area is difficult as well. However, using the fineness characteristic curves with a certain extrapolation, the specific surface area of a kernel can be defined and estimated as that of a big particle just started to be ground.



Fogarasi 1996

Figure 8. Storage-dry maize grits – "Empirical" specific surface area $A_{spec\ emp}$ vs. average particle size d_{mean} by mass; A_{spec0} – specific surface area of the kernels fed in

CONCLUSIONS

The best measurement of finished particle sizing is some form of *sieve analysis* but a complete sieve analysis will not only describe the average particle size but will also indicate peculiarities in the distribution, such as excessive levels of fine or coarse particles, etc. It can be stated: if simple sieving of feed materials or forages is acceptable, then the work here reported justifies use of the log-normal description.

The specific surface area of the ground material A_{spec} plays a significant role in the different comminution-energetic theories and investigations; the value of the specific surface area of a granular (powder) bulk is a fineness parameter – and, in addition, it is only a single figure of characterizing the particle fineness, however, not a simply "sensible or tactile" property in comparison with the particle size.

An apparently simple characteristic relationship (model law) exists between the two fineness parameters of grinds – specific surface area vs. any arbitrarily chosen or defined nominal particle size; however, with full knowledge of the size distribution, the calculation is refined and more accurate. The regression curve is a general hyperbola.

The deviation-property of the particle-size distribution of hammer mill products (in the forms of standard deviation, n, U, S_{gw} or S_{log} as well as m) behaves as a probability variable itself, and has an expectable value (or average value) in fixed conditions – with the same material and the same mill.

Accordingly, using the standard ASAE, after determining the expectable value of S_{log} or S_{gw} (more exactly its mean value calculated from a quite large series of ground samples) the equation can be written down as –

$$A_{st} = \frac{C'\left(\overline{S}_{gw}\right)}{d_{gw}} = \frac{Const}{d_{gw}} \qquad (cm^2) \qquad (11)$$

And this is a similitude of other fineness characteristics with different standard particle-size distribution parameters.

Acknowledgement

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