The Meaning of Micronaire

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Introduction

Micronaire is the archetypal cotton fibre characteristic, for at least four reasons.

1. It was the first objective, instrumental measure to be included in the classification system for cotton.

2. It represents an arbitrary scale of relative values, and does not directly evaluate any single physical fibre property.

3. The integrity of the scale (i.e. the calibration level) is maintained by a sophisticated empirical operation involving

   - selection of (a limited number of) cotton bales to be designated as calibration standards,
   - testing of samples from these bales for Micronaire reading by (a small number of) designated laboratories,
   - assigning the mean and standard deviation of the results to the whole bale, for each standard,
   - making small samples of the bales available to the cotton testing community, world-wide, so that each laboratory may adjust the level (calibration) of its own instrument to that of the reference laboratories,
   - organising regular international check-test exercises, in which the results of Micronaire measurements, made on samples of the same cotton by a large number of laboratories, are collected and analysed – so that each laboratory can see how it compares to the others.

4. In spite of the arbitrary nature of the measurement itself, and the empirical, circular, self-referencing nature of the calibration maintenance system, the Micronaire reading has proved to be an extremely practical and effective parameter over a long period.

It could be argued that, together with the fibre length, Micronaire is the most important and useful cotton fibre characteristic, for cotton classers and spinners. The Micronaire reading is taken as an indication of fineness (linear density) and maturity (degree of cell-wall development). For a given cotton type, a relatively low Micronaire reading is a predictor for problems in processing, generation of neps, and inefficient dyeing. Therefore, a great deal of trouble is taken, when blending cottons, to try to obtain a constant average Micronaire between laydowns, and uniformity of Micronaire within laydowns.

Interpretation of Airflow Measurements

Micronaire is an indication of the air permeability, or resistance to airflow of a cotton sample. It is measured by forcing air through a specimen of defined weight confined in a chamber of fixed dimensions [1]. Most Micronaire instruments measure the rate of airflow when the pressure drop is held constant, but a few - e.g. the IIC-Shirley Fineness and Maturity Tester

(FMT) [2] - measure the pressure drop at a constant rate of airflow. In either case, the result is converted to a Micronaire reading, either by means of a calibrated scale on the instrument or by a suitable conversion formula, or by integrated software.

Originally, the Micronaire scale was arrived at, and subsequently adjusted [3], to correlate with the average fibre linear density (in μg/inch) determined by the ASTM array method [4]. However, it was subsequently found that the correlation with fibre fineness was not very satisfactory and the unit μg/inch was dropped [5]. *Figures 1 to 3* show examples of the relationship between Micronaire and fibre fineness. The data in *Figure 1* are taken from a USDA research publication [6], where fineness was determined by the ASTM reference array method. The data of *Figure 2* are taken from Lord [7], where fineness was measured by the British method [8] and has been converted to μg/inch. The data of *Figure 3* are taken from the Bremen Round Test results since 1978 [9], where fineness was estimated with the FMT and has been converted to μg/inch. Although the correlations are good to very good, the slopes and offsets are unacceptable and the actual deviation from the trend line of many of the samples is too great. Nevertheless, the terminology has persisted in many areas and one still can find references to Micronaire units of μg/inch.

Pioneers in the interpretation of airflow measurements on textile fibre plugs were Hertel [10] and Lord [11]. Hertel, in connection with the development of the Arealometer instrument, and Lord, in a thorough review of airflow through fibre plugs, showed that the relationship arrived at by Kozeny [12] and by Fair and Hatch [13] can be suitably modified to provide an accurate description of airflow through cotton fibres.

One formulation of this relationship is the following.

$$Q / \delta P = K.I \; . \; 1 / So^2 \; . \; \varepsilon^3 / (1 - \varepsilon)^2 \qquad (1)$$

where,

- Q is the rate of airflow.
- δP is the pressure drop across the sample.
- K is a constant, for a given experimental set-up, mainly determined by specimen orientation and fibre type (average shape of cross section).
- I is an instrument constant containing the dimensions of the chamber and the viscosity of the air.
- So is the average fibre specific surface, i.e. the perimeter of the fibre cross section divided by the area of the whole fibre cross section, including lumen.
- ε is the specimen porosity, i.e. the proportion of the chamber volume occupied by the fibres.

The specimen porosity, ε, is given by the weight of the specimen multiplied by the average specific volume of the fibres divided by the volume of the chamber. If we can assume, for the time being, that the average specific volume of cotton fibres is approximately the same for all growths, and that the weight of the specimen is held constant, then the last term can be included into an instrument / environment constant, and

$$Q / \delta P = C / So^2 \qquad (2)$$

where,

$C = K \,.\, I \,.\, \varepsilon^3 / (1 - \varepsilon)^2$

Thus, to a first approximation,

- measurements of the rate of flow, *Q*, should be directly related to the inverse square of the Specific Surface, $1/So^2$, and
- measurements of the pressure drop, δP should be directly related to the square of the Specific Surface, So^2.

Hertel and Lord both showed that airflow instruments in general closely follow this relationship although, of course, any given instrument has to be calibrated to take account of the specific experimental conditions embodied in *C*. In particular, Lord confirmed the expected strong correlations between airflow and pressure drop, and between airflow and $1/So^2$. More recently, Heap [14] has shown that the IIC-Shirley FMT instrument also obeys the same general rules to a high degree of precision.

Specific Surface, Fineness and Maturity

Specific surface is the perimeter of the fibre cross section divided by the area of the whole fibre cross section, including lumen. If we set P = fibre perimeter and At = the total area of the whole fibre cross section, then

$$1 / So^2 = (At / P)^2 \qquad (3)$$

Thus, *Q*, the airflow at constant pressure drop – and hence the Micronaire Reading - should be directly proportional to the square of fibre cross sectional area and inversely proportional to the square of fibre perimeter.

By making a few simple assumptions, we can easily see how the original supposition arose, that Micronaire was directly related to fibre fineness.

- An individual, pure strain, cotton variety shows a rather small variation in average fibre perimeter between samples. It is not a very large departure from the truth to assume that cottons of closely similar types (e.g. Upland cottons grown in the 1950s and 1960s) have very similar average perimeters, one to another.
- For the same group of Upland cottons, the average proportion of the fibre cross section occupied by the lumen is, presumably, more or less the same. In any case, the average area of the lumen is a relatively minor proportion of the area of the whole section. Fibre fineness is simply the area of the fibre cell wall (i.e. cross sectional area minus lumen area) multiplied by the average cell wall density.
- For the same group of Upland cottons, if the average cell wall density is about the same, then At is proportional to fibre fineness.

Thus, for an individual, pure strain cotton variety, and hence (approximately) for a group of closely related cottons, with more or less constant perimeter, the inverse square of specific surface is directly proportional to the square of fibre fineness.

Figure 4 shows two subsets of the Bremen Round Test data, in which the fibre perimeters were calculated to be between 48 and 50, or 52 and 54 micrometres, respectively.

If practical experience is gained with processing a particular type of cotton, so that the optimal value for its Micronaire reading is well known, then a sample of that type, which presents a relatively low Micronaire reading can be assumed to have a relatively low linear density. Since the fibre perimeter probably has not altered by much, this can also be taken as a relatively low level of maturity. This is the basis for the enormous practical value of the Micronaire reading for trade and industry. In effect, a relatively low Micronaire value is signalling a low maturity.

In general, however, the Micronaire Reading will not correspond to the actual fineness in μg / inch unless the particular variety being measured has a fibre perimeter, which corresponds to the average of those that were used in the construction of the Micronaire scale.

It was only when cottons with a much greater genetic diversity, and hence a greater range in fibre perimeter were examined that the apparent link between Micronaire and fibre fineness was broken.

Micronaire, Fineness and Maturity

It can easily be shown that, for an individual fibre, the inverse square of fibre specific surface is directly proportional to the product of fineness and maturity.

If we define maturity as the degree of secondary wall thickening, θ, [2, 8, 17, 19], then

$$\theta = 4 \pi Aw / P^2 \quad (4)$$

or

$$P^2 = 4 \pi Aw / \theta \quad (5)$$

where,

Aw is the cell-wall area (cross-sectional area minus lumen area).

If we then set ν = whole fibre specific volume, ρ = cell wall density, and H = fibre fineness, in mtex, then

$$\text{At} = H \nu \quad (6)$$

and

$$\text{Aw} = H / \rho \quad (7)$$

Substitution of (6) and (7) into (5) and (3), leads to

$$1 / So^2 = \theta H . \rho \nu^2 / 4 \pi \quad (8)$$

By convention, the Maturity Ratio, M, is taken as unity when θ = 0.577. Reasonable values for the average fibre specific volume and the average cell wall density are 0.75 and 1.52, respectively. Substitution of these values into (8) yields

$$1 / So^2 = MH / 25.472 \quad (9)$$

Thus, Q, the airflow at constant pressure drop, should be directly proportional to the product of Fineness and Maturity, MH.

Since the Micronaire reading is a transformation of the airflow at constant pressure drop, for a fixed set of experimental conditions, then there should be a direct relationship between Micronaire and the product MH, which encompasses the instrument constants, the experimental conditions, and the arbitrary transformation built into the Micronaire scale.

If this is can be substantiated experimentally, then it is very important, for (at least) two reasons.

1. It provides a way of linking Micronaire readings directly with particular fibre properties.

2. It holds forth the possibility of providing an objective calibration for the Micronaire instrument, traceable to direct measurements of the Specific Surface.

Therefore, some attention will be paid to substantiating this general relationship.

In a detailed evaluation of the Micronaire instrument, Lord confirmed that, for a set of 100 cottons, the relationship between MH and Micronaire (Mic) could be described by the following formulation [7].

$$MH = 3.86\,Mic^2 + 18.16\,Mic + 13.0 \qquad (10)$$

with a correlation of $R^2 = 0.9809$.

Using a limited range of cottons - the International Calibration Cotton Standards (ICCS) - Heap has shown [2] that a similar relationship exists for the corresponding parameters estimated with the IIC-Shirley FMT instrument.

$$Mat.Fin = 2.07\,Meq^2 + 32.09\,Meq - 12.68 \qquad (11)$$

with a correlation of $R^2 = 0.998$.

Lord's and (a sub-set of) Heap's original data have been re-examined and it was found that (10) and (11) can be slightly simplified, with negligible loss in the correlations, by forcing the curves to pass through the origin.

$$MH = 3.32\,Mic^2 + 23.67\,Mic \qquad (12)$$

with a correlation of $R^2 = 0.9808$ (*Figure 5*), and

$$Mat.Fin = 2.55\,Meq^2 + 26.90\,Meq \qquad (13)$$

with a correlation of $R^2 = 0.9997$.

Very high correlations between Mat.Fin and Meq are to be expected from the FMT, of course, because of the way that these parameters are all calculated from the two pressure-drop measurements. Furthermore, these particular Mat, Fin, and Meq values are the averages from five separate FMT instruments, and the range of cottons is a very special one – the calibration standards. When Heap's data were examined using Micronaire instead of FMT Meq, then the following relationship was found.

$$Mat.Fin = 2.76\ Mic^2 + 25.56\ Mic \quad (14)$$

with a correlation of $R^2 = 0.9985$ (*Figure 6*).

Thus, the expected good correlations between Mic and MH, or Mat.Fin appear to have been substantiated, and to a high level of precision. However, Lord's measurements were made more than four decades ago, and Heap's data are of a limited and very special nature. Therefore, it is worthwhile to see if additional confirmation can be found from the more recent literature.

There are two additional literature sources, which can provide a useful check on the relationships between Mic and MH or Mat.Fin.

Mitchell [15] has reported both MH and Mat.Fin data for a range of 30 cottons. Analysis of his data results in the following relationships.

$$MH = 3.23\ Mic^2 + 23.21\ Mic \quad (15)$$

with a correlation of $R^2 = 0.9876$ (*Figure 7*), and

$$Mat.Fin = 2.69\ Mic^2 + 26.09\ Mic \quad (16)$$

with a correlation of $R^2 = 0.9968$ (*Figure 8*).

The close agreement between equations (12) and (15) not only substantiates Lord's original analysis but also suggests that the Micronaire instrument calibration had remained substantially constant over the intervening period. However, it should be pointed out that a certain number of Mitchell's cottons were taken from the same source as Lord's (the Shirley Institute cotton library).

A more independent set of data is provided by the results of the Bremen Round Tests [9]. The Bremen Fibre Institute has carried out round tests for several decades, in which many laboratories test samples of the same cottons. Micronaire has been included in these round tests from the beginning and the FMT instrument has been included since the middle 1970's. Because the mean of all laboratories is statistically secure, and because it represents the actual situation in the field – with many different types of laboratories (and different types of Micronaire instruments) - these data are particularly valuable.

Analysis of the Micronaire and Mat.Fin data from the round tests has been carried out for the period 1978 – 1999 (72 cottons), with the following result.

$$Mat.Fin = 2.53\ Mic^2 + 26.86\ Mic \quad (17)$$

with a correlation of $R^2 = 0.990$ (*Figure 9*).

Equations (14), (16), and (17) are almost indistinguishable over the range of interest (*Figure 10*) and, when given equal weight, produce the following relationship.

$$Mat.Fin = 2.66\ Mic^2 + 26.17\ Mic \quad (18)$$

It seems safe to assume that the Micronaire reading is a pretty accurate reflection of the whole fibre specific surface, and hence the product of fibre linear density and Maturity Ratio. Unfortunately, the relationship is an empirical one, forced by the (more or less) arbitrary transformation of the measured airflow into the Micronaire scale and the choice of a constant value for all cottons of the average fibre specific volume. Small differences in the various regression equations (if, indeed, they are at all significant) may be to do with the particular set of cottons that is included and may indicate that the fibre specific volume is not quite constant for all cottons. In fact, Neelakantan has argued for such differences [16], and Lord has noted [2] that some cottons consistently return anomalous results, when measured on the FMT, indicating that other fibre properties besides fineness and maturity can play a significant role in the interpretation of airflow measurements.

Calibration of Airflow Instruments

Until very recently, it was unthinkable that the Micronaire instrument (or the FMT) should be calibrated properly, using direct measurements of fibre specific surface, or fibre linear density and maturity. Although linear density may be estimated quite accurately, in a reasonable time (for research purposes), by one or other of the reference gravimetric methods, the direct measurement of specific surface or maturity – by cutting and measuring fibre cross sections – was prohibitively expensive and subject to considerable operator error. However, developments in the techniques for making fibre cross sections, and for measuring these using image analysis have been impressive in the last few years [17, 18, 20].

With image analysis systems the fibre perimeter and the area of the whole fibre cross section can be measured relatively easily and accurately. The specific surface, So, is given by the ratio of perimeter to whole fibre area so, in principle, it is now possible to calibrate airflow instruments directly, so that they can deliver an estimate of specific surface that should be relatively accurate and traceable to a direct reference method.

Image analysis also allows the measurement of the area of the fibre cell wall and hence, by assuming a value for the average density of the cell wall, an estimate for fibre linear density. It should be noted that, although the value for fineness so derived refers to nominally random fibre sections, with the current specimen preparation techniques the longer fibres are probably over-represented. This is different from either the ASTM array method or the British method, but might be quite similar to an airflow measurement, in which the longer fibres are probably also over-represented.

Maturity also can be calculated from the cell-wall area and the perimeter. For this purpose, maturity must be defined in fundamental terms, as the degree of secondary wall thickening, θ. The Maturity Ratio, if required, is calculated from the (arbitrary) convention, originally proposed by Pierce & Lord [2, 8], that Maturity Ratio is taken as unity when $\theta = 0.577$.

It can be argued that a proper calibration of the Micronaire instrument is unnecessary and even counter-productive, because of the apparent stability of the Micronaire calibration over several decades and the wide familiarity of the cotton marketing and processing industries with the *practical* interpretation of the Micronaire scale of values.

Nevertheless, there seems little doubt that direct measurements of fibre cross sections, using image analysis, will be required for calibrating airflow (and other) instruments which

measure maturity [2, 20]. Therefore, the additional effort needed to provide a direct calibration for Micronaire instruments will be trivial and could provide significant benefits. Ideally, direct calibration should be made against the whole-fibre specific surface and we can perhaps assess the potential for such calibrations by checking whether image analysis measurements of specific surface, fineness and maturity conform to the expected relationships with Micronaire reading.

Unfortunately, measurements of the whole fibre cross section area are not usually made by image analysis because, until now, the objective of such work has been to estimate fineness and maturity. Therefore the only relationship that can be examined, at present, is that between Micronaire and the product of fineness and maturity, as determined by image analysis. Thibodeaux has made one such comparison [18], and concludes that his image analysis estimates of fineness and maturity are at least consistent with the relationship of equation (10).

Thibodeaux has kindly made available further data (published at this conference), which include Micronaire readings as well as image analysis measurements of cell wall area and fibre perimeter. When these new data are combined with those of the earlier publication, the following relationship emerges, where Imat and Ifin are the maturity and fineness derived from image analysis of fibre cross sections.

$$Imat.Ifin = 1.89\,Mic^2 + 32.97\,Mic \qquad (19)$$

with a correlation of $R^2 = 0.917$ (*Figure 11*).

The three equations, (12), (18), and (19) yield very similar results, as can be seen from *Figure 12*. To the (rather doubtful) extent that the curves may be significantly different, one may perhaps speculate that the relationships derived from Mat.Fin and Imat.Ifin data seem to be almost parallel, over the range of interest. They might be made to coincide by a suitable choice of fibre density for the image analysis calculation of fineness. Lord's equation straddles the other two and might reflect the fact that the British method for fibre fineness determination is (almost) not length-biased and involves only the central portions of the fibres, whereas both image analysis and FMT measurements may be somewhat length-biased and involve the whole fibres. Note, however, that the original calibration for FMT Fin was in terms of the British method for measuring fibre fineness [2].

Taken as a whole, these results suggest that it should be possible to provide a more or less precise, direct calibration of airflow instruments, such as Micronaire or FMT, in terms of a single fibre property, namely the specific surface. Specific surface, the ratio of fibre cross section perimeter to whole-fibre cross section area, can be rather easily measured by image analysis. For individual cottons, the actual average fibre specific volume can be established by comparing image analysis measurements of whole fibre cross sections to direct, gravimetric measurements of average fibre linear density.

Once a direct calibration has been provided, in terms of specific surface and specific volume, the relationship between airflow and the product of fineness and maturity, can be scrutinised with greater rigour than has been possible up to now. Such scrutiny could prove to be extremely valuable for researchers and instrument manufacturers, who are striving to produce better, more rapid methods for measuring fineness and maturity. In addition, it should be possible to deduce, once and for all time, what is the "true" relationship between fibre

specific surface and Micronaire value, and hence to provide a “hard” calibration for Micronaire.

For this purpose, reliable estimates of the true whole-fibre density and the cell-wall density may be required. In addition, it may be advisable to specify a constant geometry for airflow instruments – otherwise every type of instrument has to be separately calibrated, because of differences in the instrument / environment constant, *C*, in equation (2).

Finally, it may be important to establish whether the relatively greater scatter in image analysis estimates of the product fineness.maturity, compared to FMT estimates, is random or systematic. A greater level of random scatter is perhaps to be expected at this stage in the development of the image analysis procedure. The available data have been collected during a period when great improvements were being made to the procedures, and improvements are still being made. Systematic scatter could be introduced, for example, by the assumption of a constant cell-wall density for all cottons, when calculating fineness from cell-wall area.

If the extent of any systematic scatter can be quantified, and allocated to its proper source, then this will provide the baseline for the ultimate accuracy of image analysis measurements of fineness and, by extension, the fundamental limitations to the accuracy of airflow devices, however calibrated. For this purpose, the image analysis procedure will have to be calibrated against an appropriate reference gravimetric fineness procedure.

Conclusions

The Micronaire scale is essentially a more or less arbitrary transformation of an air permeability measurement.

For an individual, pure strain cotton variety and, to a lesser degree, within a group of cottons of closely related varieties, the Micronaire Reading is directly related to fibre fineness, and hence to fibre maturity, but it does not indicate the actual fineness in μg / inch.

In general, for the whole range of commercial cottons, the Micronaire reading can not be taken as a measure of either fibre fineness or fibre maturity alone.

From the basic theory, Micronaire is expected to be directly related to the inverse square of the average fibre specific surface, moderated by the (arbitrary) transformation, which converts airflow (or pressure drop) to Micronaire reading, and the experimental conditions of the particular airflow instrument used.

The inverse square of the fibre specific surface is directly related to the product of fineness and maturity, moderated by the whole-fibre density.

Therefore Micronaire should be directly related to the product of fineness and maturity. The extent of the effect of differences in whole-fibre density between cottons of different growths is not known, but it seems to be rather small.

Examination of several data sets, where both fineness and maturity have been estimated by different methods, has confirmed that the expected relationship between Micronaire and the product of fineness and maturity is obeyed rather faithfully. This includes estimates of fineness and maturity obtained by image analysis.

Image analysis should be capable of providing direct calibrations for airflow instruments, in terms of the average fibre specific surface. Several benefits can be envisaged to flow from such a "proper" calibration, not only for Micronaire measurement, but also for the determination of fibre fineness and maturity.

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Figure 1

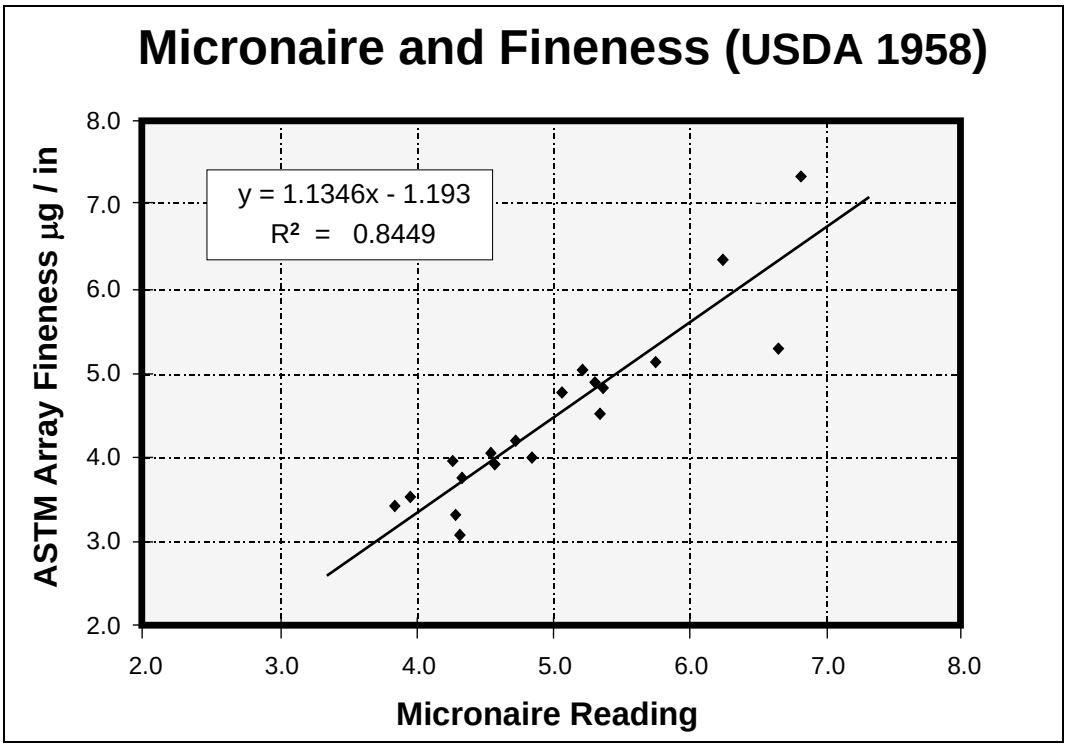


Figure 2

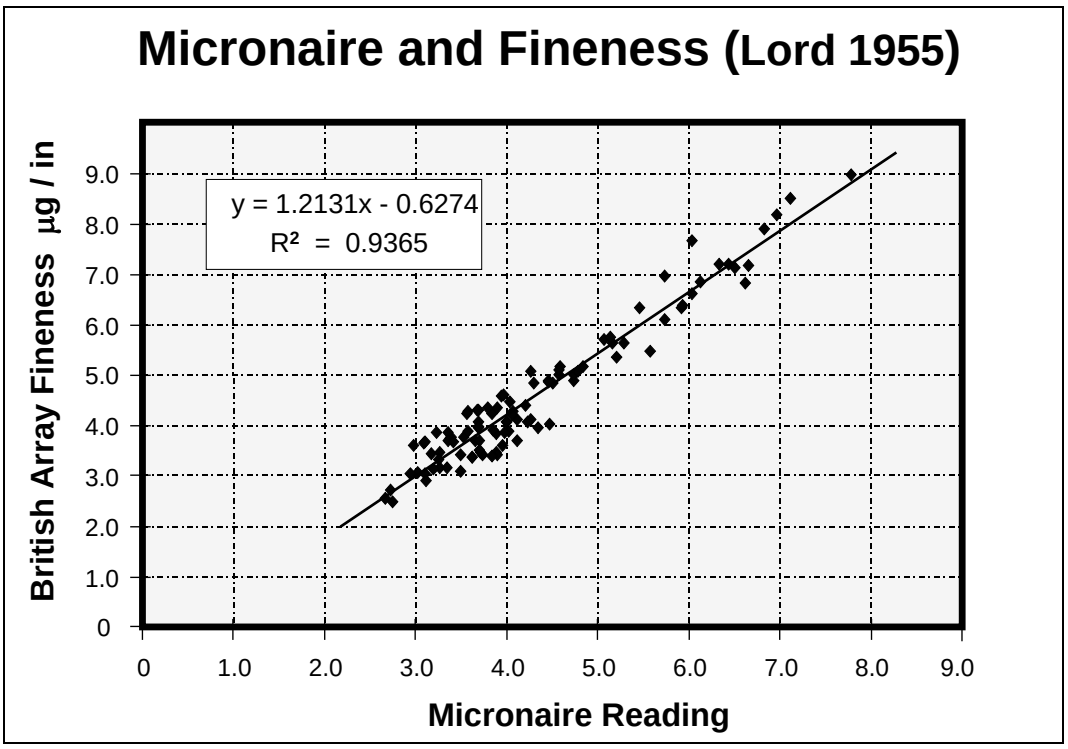


Figure 3

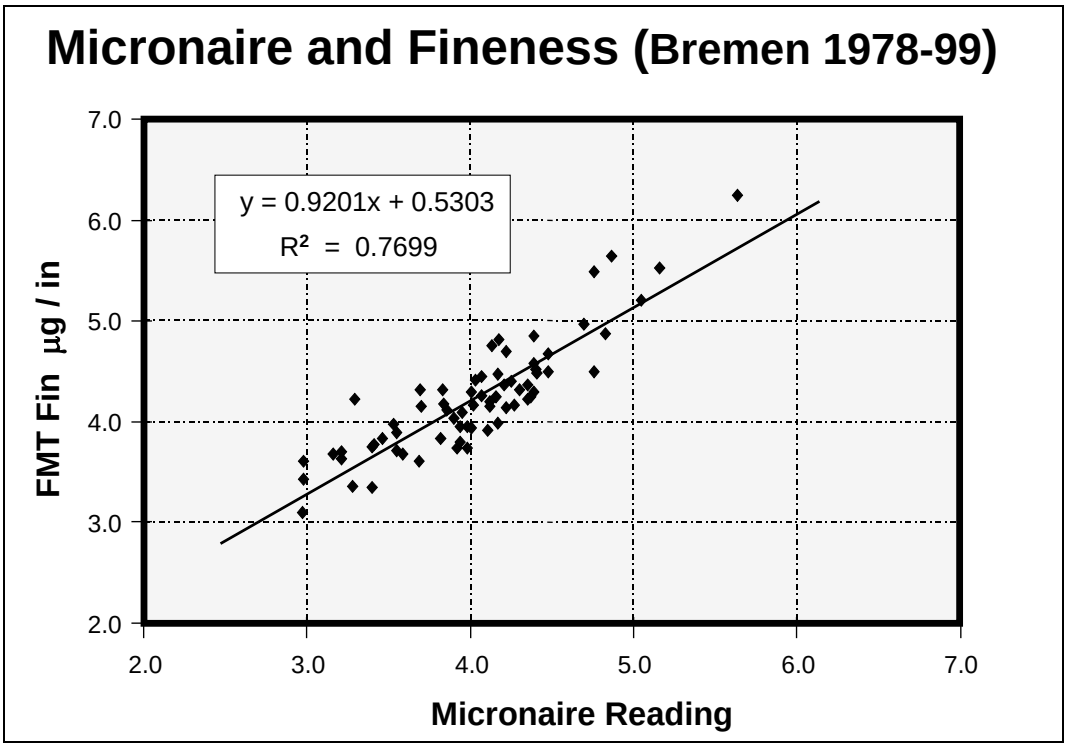


Figure 4

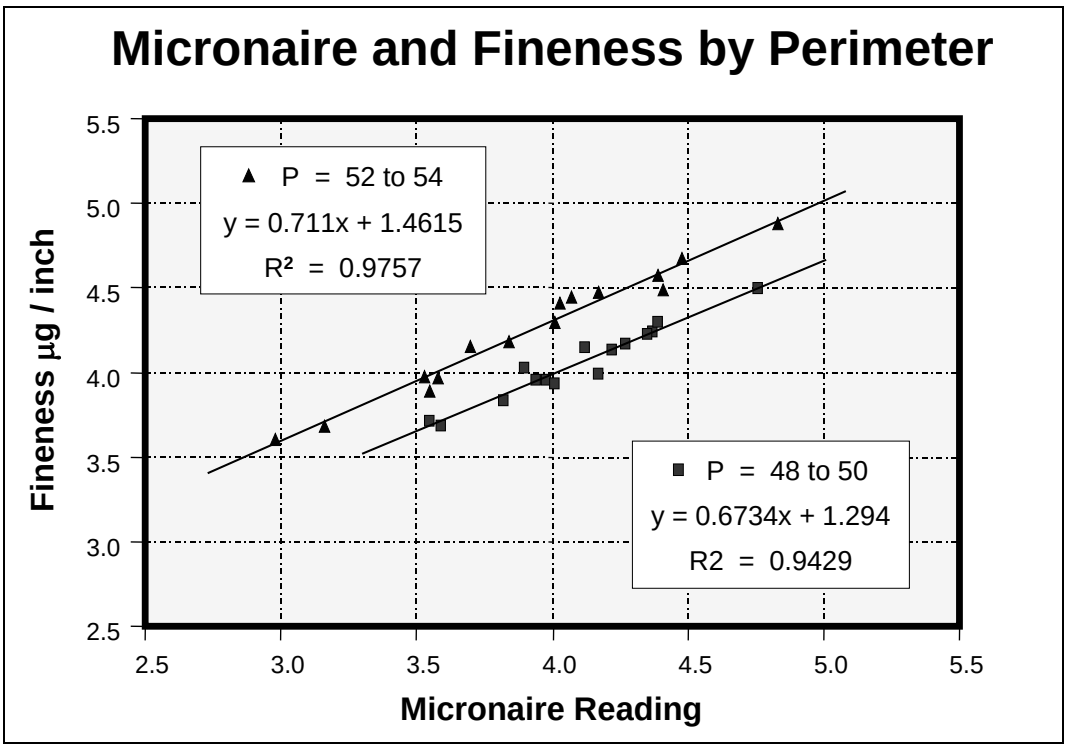


Figure 5

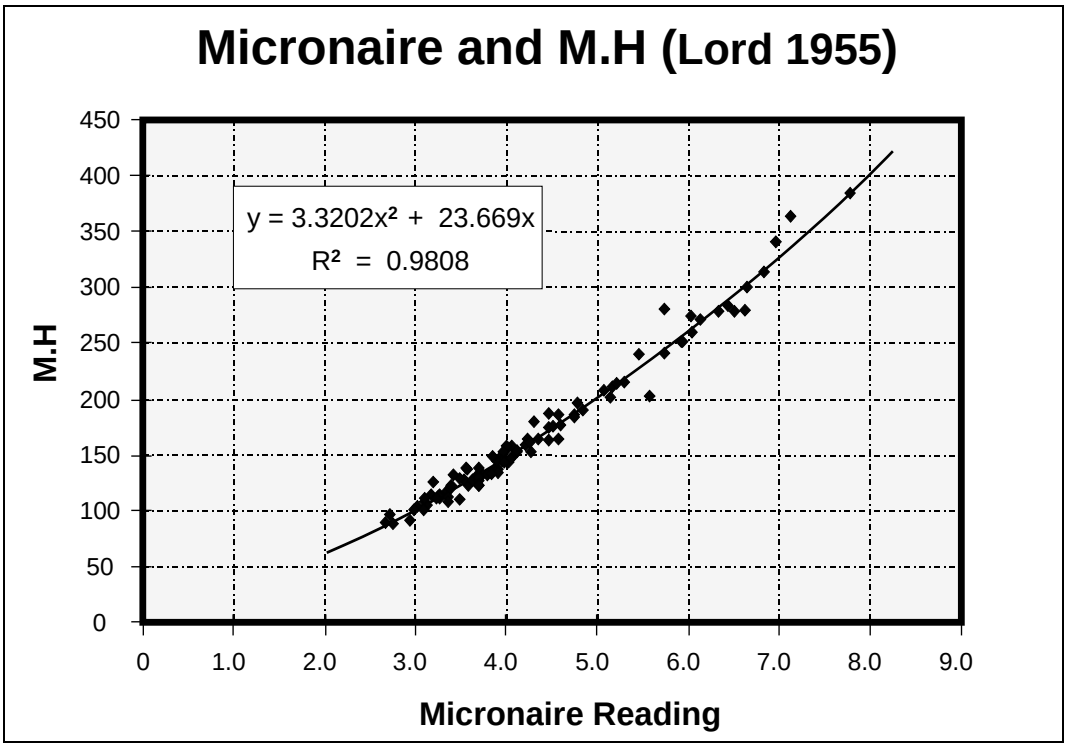
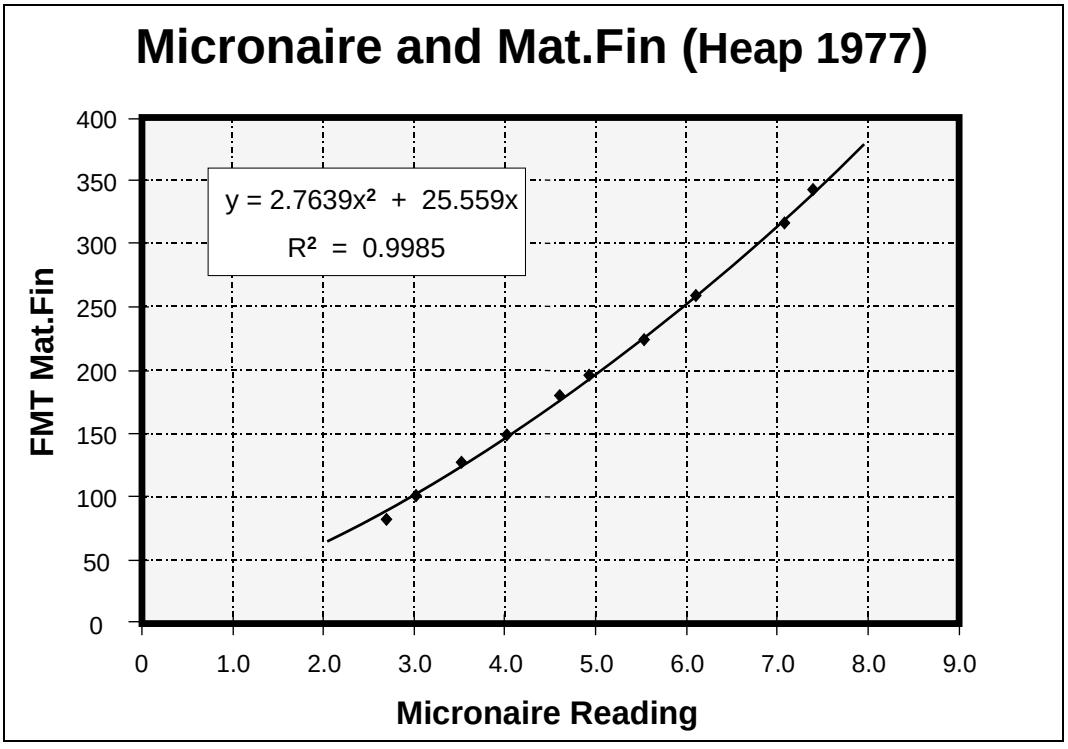


Figure 6



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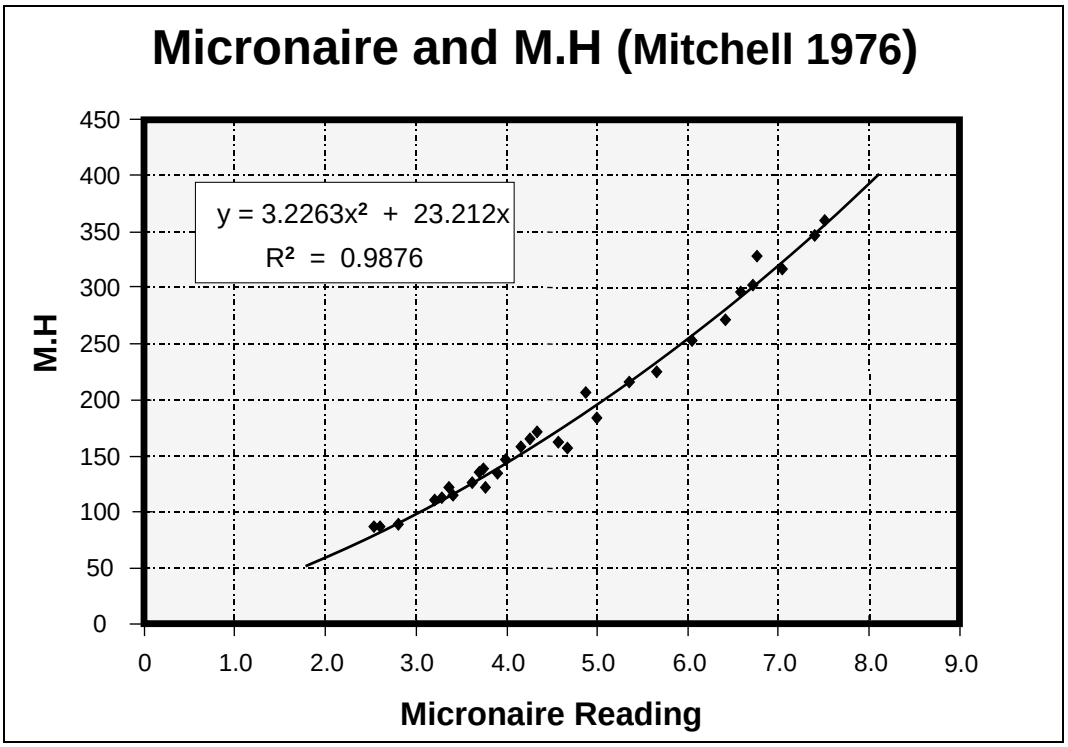

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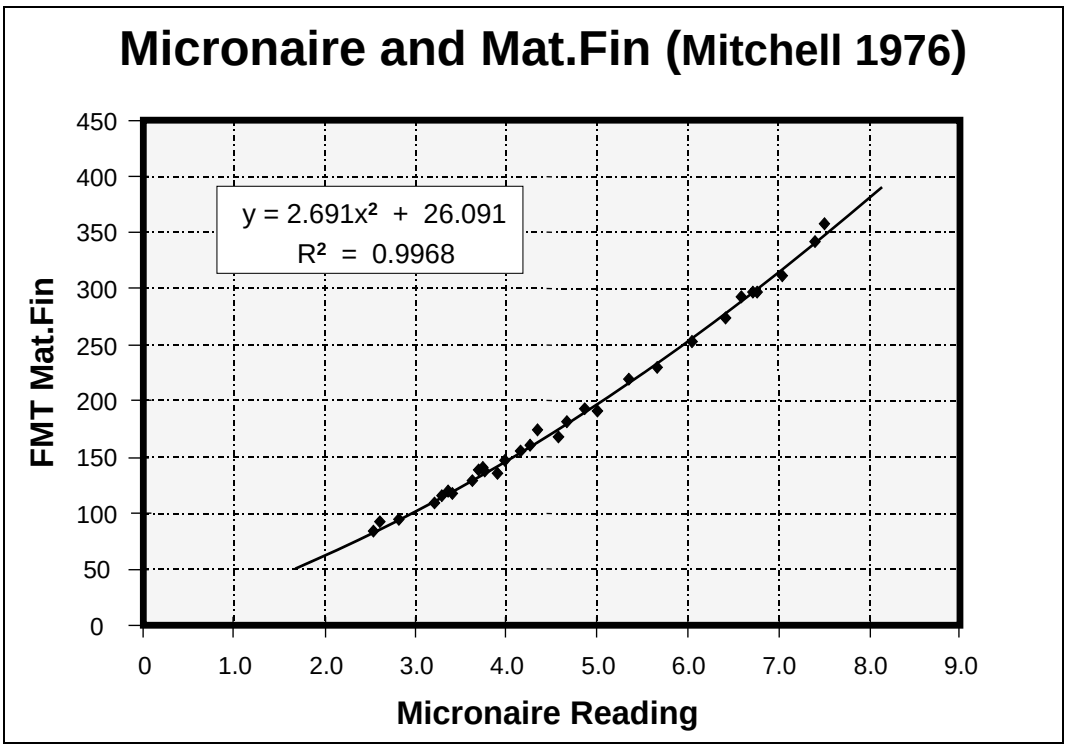

Figure 9

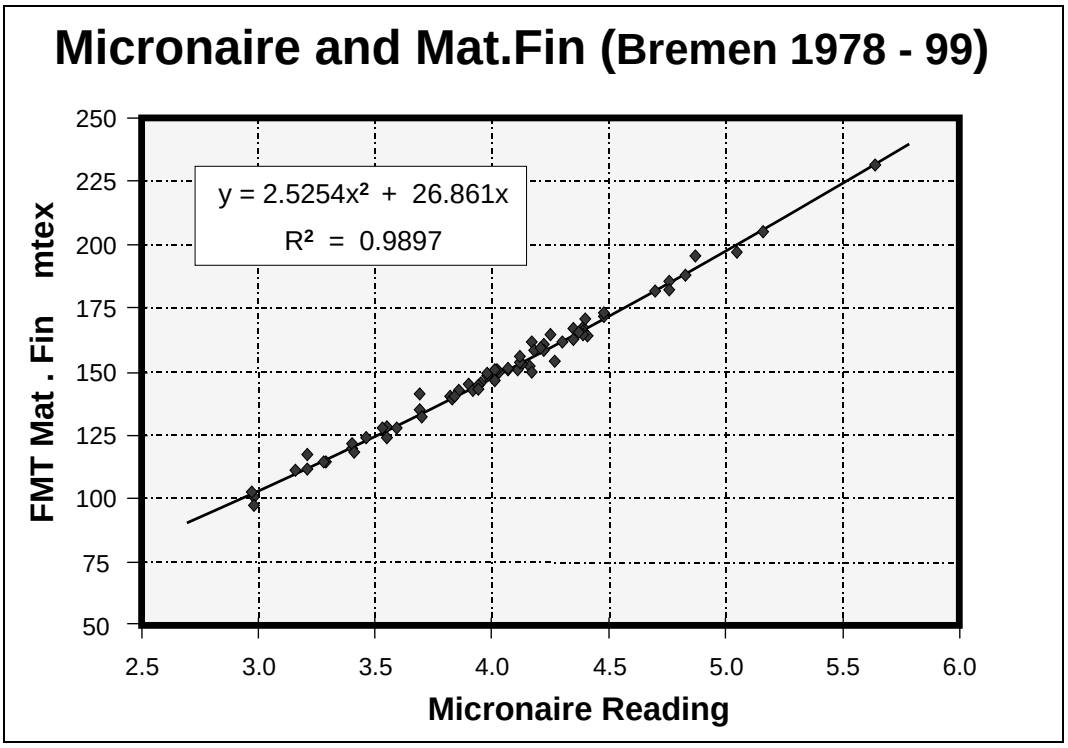

Figure 10

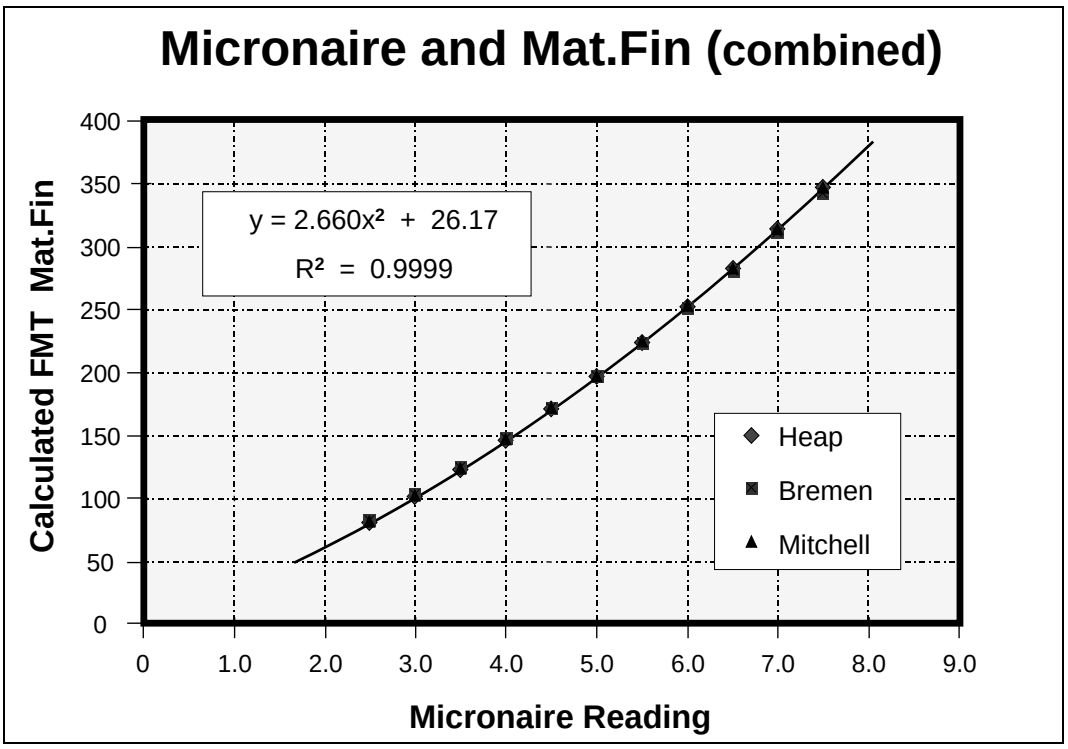

Figure 11

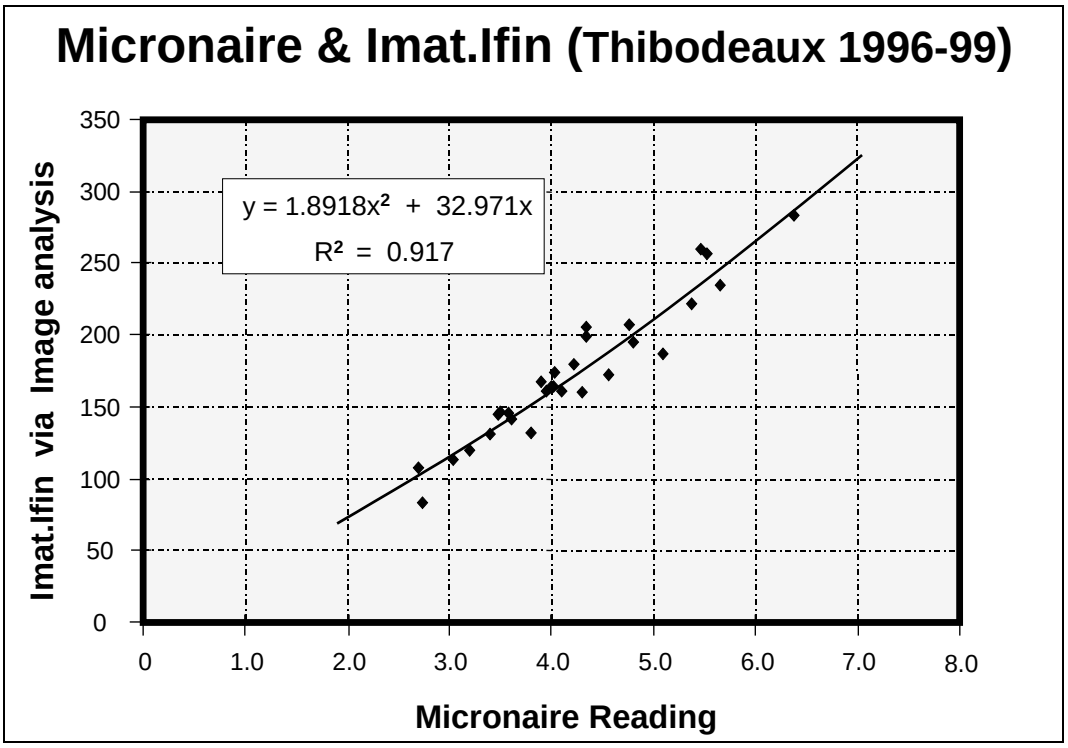

Figure 12