A DEVICE FOR RAPIDLY PREDICTING COTTON LINT MOISTURE CONTENT

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ABSTRACT. The moisture content (MC) of cotton lint can be predicted from measurements of electrical resistance. New, automated, resistance-type moisture meters for cotton make measurements in less than 1 s using DC excitation. The sample resistance changes rapidly during the first 10 s of the measurement, making conclusions based on older measurement technology, which took several seconds, questionable. Thus, a device capable of making measurements in less than 1 s and using DC excitation was designed, built, calibrated, and tested. Data showed that the device could measure the electrical current through the samples precisely and that the current was related to the sample moisture content. Regression analysis showed that the standard error in predicting MC was 0.20% over the range 4.1% to 8.7% (wet basis). The types of plastic tested for the sample holders did not affect the resistance. A strong relationship was found between the sample resistance and the sample density over the range of 0.4 to 1.4 g/cm³.

Keywords. Cotton, Density, Electrical resistance, Instrument, Lint, Measurement, Moisture content.

The moisture content (MC) of cotton fiber materially affects the cleaning performance of the gin and the damage done to the fiber by the gin plant (Anthony, 1990). Incoming seed cotton contains varying amounts of moisture, and moisture control is one of the major tasks of the gin. Thus, an accurate, reliable, and inexpensive method to measure MC is needed to facilitate moisture control.

Electrical resistance-based moisture meters have been used for measuring cotton fiber MC for many years. During the 1960s and early 1970s, data were collected at the Cotton Ginning Research Unit in Stoneville, Mississippi, by A. C. Griffin on the basic operating parameters of resistance moisture meters. These studies were recorded in annual reports but were never published (Griffin, 1963–1973). Griffin measured the resistance of cotton lint samples by manually reading an analog voltmeter in a circuit with fixed resistors using 200 VDC excitation. He found that the resistance of the cotton sample decreased with increasing mass density, although variations in density over a wide range (0.25 to 1.2 g/cm³) affected the measured resistance less than a change of 1% MC would. He found that defoliants, insecticides, and herbicides have measurable but small effects on the resistance, and that trash levels have almost no effect on the measured resistance. He also found that the measured sample resistance changed for some time after the sample was compressed. He used the reading obtained 30 s after sample compression and electrical excitation in subsequent analyses. Figure 1 shows one set of data from Griffin and Collins (1971) of the resistance of a cotton lint sample 1 cm thick and 1 cm² in area at 6.4% MC recorded during the first 10 min after excitation with 200 V. The first point recorded was at 15 s after compression and electrical excitation.

Byler (1998) described several studies of the electrical conduction properties of cotton fiber samples, and the work resulted in a patented moisture meter (Byler and Anthony, 1996). This patent has been licensed to Uster Technologies by the USDA, and a moisture meter based on the patent is commercially offered as a component in “IntelliGin” for gin process control and “Spectrum” for fiber properties measurement. The apparent resistance was found to decrease rapidly after sample compression during the first few minutes of the test and did not stabilize for about 15 min (Byler, 1998). Byler (1998) recorded the resistance readings manually based on 50 VDC excitation with an analog MΩ meter using the

![Figure 1. Resistance of a lint sample at 6.4% moisture content measured by Griffin and Collins (1971) during the first 10 min of excitation at 200 VDC.](image-url)
reading obtained 4 s after sample compression and electrical excitation. An automated moisture meter would be expected to complete a measurement in no more than a few seconds, but laboratory resistance readings could not be made in that time with the analog Meg–ohm meter.

A model of the following form was found to fit the resistance–moisture data well for cotton lint (Byler, 1998):

$$R = Ae^{BM}$$  \hspace{1cm} (1)

where

- $R$ = observed resistance (Ω) recorded 4 s after sample compression
- $M$ = moisture content of the cotton sample (% w.b.)
- $A$ and $B$ = parameters chosen by regression.

A sensing system that linearized this relationship by taking the logarithm of the resistance would simplify the relationship.

The cotton sample holders used by Byler (1998) were made of acrylic, which have a conductivity on the order of $10^{-12}$ S/m, but other plastic materials may be better, such as polytetrafluoroethylene (PTFE or Teflon) and ultra–high molecular weight polyethylene (UHMWPE). PTFE has very low conductivity, on the order of $10^{-16}$ S/m, so it is often used for applications where low electrical current leakage is required (Giacolletto, 1977). UHMWPE also has very low conductivity, on the order of $10^{-14}$ S/m, and is much less expensive than PTFE. PTFE has a higher working temperature than acrylic or UHMWPE and may be better for use in gins, where fires occasionally occur.

The purpose of this study was to develop and construct a laboratory instrument capable of rapidly measuring the moisture content of a cotton lint sample at different densities based on the sample electrical resistance to DC excitation.

**Materials and Methods**

The cotton resistance meter consisted of a sample container, a sample container holder/compressor, a power supply to impress a voltage across the sample, a current–to–voltage converter (I/V), and a computer with an analog–to–digital converter (fig. 2). Three identical sample containers were constructed, except that one was made of acrylic, another of PTFE, and the third of UHMWPE. Each plastic unit was a cylinder 4 cm in diameter and 3 cm high. A hole, 1 cm² in area, was drilled in the plastic cylinder. An aluminum face, 8 mm thick, was fastened to the bottom of the cylinder. An aluminum cap with a rod, 1 cm² in size, was fit to the top. The rod extended 2 cm into the hole in the plastic cylinder. When the cap was completely inserted into the holder, the space for the cotton sample was 1 cm² by 1 cm high.

The holder/compressor had a solenoid–controlled air cylinder attached to an aluminum disk 4 cm in diameter, which matched the top of the sampler container. The aluminum disk was electrically isolated from the solenoid by a PTFE gasket and was connected to the +12 VDC on the power supply. When a test was to be run, the sample container was placed on an aluminum platform that was isolated from the holder/compressor by a PTFE pad and was connected to the positive pole of the current port of the I/V.

The I/V is a logarithmic converter (model DN120, Dawn Electronics, Inc., Carson City, Nev.). This transducer has a linear output voltage from 0 to 5 V based on the natural logarithm of an input current from 10 fA to 100 μA (Phalan, 1998). The DN120 uses a temperature regulator to hold the logarithmic converter diodes at 23°C to prevent ambient temperature variations from affecting the conversion (Phalan, 1998). The thermoelectric cooler in the DN120 requires 10 min to “warm up.” The room where the data were collected was maintained at 22°C ±2°C, well within the design range for the DN120 of 23°C ±5°C. A 16–bit A/D converter with a range of 0 to 5 V was used. This arrangement resulted in a resolution of 76 μV, while the DN120 output resolution is 1 mV (Dawn Electronics, 1996).

A cotton resistance measurement cycle was completed by weighing the cotton lint needed for a test, often 1 g, placing the lint in the hole in the plastic container, and then inserting the rod of the cap into the container. The container was then placed in the holder/compressor, and a computer key was pressed to start the electrical measurement. Gloves were worn while handling the lint, and the transfers were made in the laboratory as quickly as possible. The transfer was always made in less than 1 min. The computer controlled a voltage that activated the solenoid, which caused an air cylinder to compress the container and the sample within. The air cylinder ensured that firm contact was made between the electrodes on the top and bottom of the sample holder, which

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![Figure 2. Schematic of sample resistance measurement system.](image-url)
were connected electrically to the remainder of the current loop. The computer then used the computer’s clock to determine when to collect measurements by reading the A/D converter at programmed intervals. For this study, one A/D reading was taken 0.7 s after the air cylinder was activated. The A/D output was recorded to the computer’s hard drive along with identifying data for the observation. The 0.7 s delay was chosen to allow for transients, due to sudden mechanical and electronic changes occurring when the sample was clamped, to decay but still to be less than 1 s.

It was necessary to carefully shield all portions of the current loop for accurate measurement of the low current. A sheet metal box was built around the sample holder and contact plates. Shielded cables were used between the power supply and the top contact plate and between the bottom contact plate and the I/V converter. As purchased, the I/V converter was contained in an aluminum box, which acted as a shield. One side of the sheet metal box was removable with magnets to hold it in place. This arrangement simplified loading and unloading of the sample container into the holder/compression unit while keeping the system completely shielded while measuring current.

CALIBRATION USING FIXED RESISTORS

A set of 13 high-resistance, high-stability, hermetically sealed resistors distributed over the range 300 kΩ to 100 GΩ was assembled for checking the operation and calibration of the current measuring circuit. The 12 VDC excitation was checked using a 4–1/2 digit digital voltmeter. The 12 VDC excitation would result in currents over the range of 40 μA to 120 pA, well within the specified range of the DN120. The worst-case conditions for the I/V converter were at the lowest current. At 100 pA, the specified current accuracy was ±2 pA and the rise time was 15 ms (Dawn Electronics, 1996). While testing with cotton over the following four months, a subset of seven of the resistors was measured twice on 22 separate days. These readings were used to check that the calibration remained valid.

CALIBRATION OF SAMPLE CURRENT COMPARED TO OVEN MOISTURE CONTENT

Cotton lint samples were stored for at least one week in three chambers where different but relatively constant moisture conditions were maintained. Two of these chambers used a salt solution in water to maintain the relative humidity, and the third had mechanical temperature and relative humidity controls. Previous work (Byler, 1998) showed that it was difficult to measure cotton lint MC below 3.5% by measuring the electrical current because the resistance becomes so high. Drying is done in the gin to bring the lint MC to below 7%, and the recommended level for ginning is 6% to 7% (Hughes et al., 1994). It would be unusual for lint to be ginned with a MC much more than 7%, and when the lint has a MC below 5% no drying is necessary. Considering these factors, the target MC range for this study was from 4% to 8%.

Samples were taken from a chamber for use in the testing and were immediately placed in metal cans with tight-fitting lids. Subsamples were taken from the cans for testing in the experimental apparatus, and 20 grams of the remaining cotton was used for a wet basis (w.b.) moisture content determination by the oven method (Shepherd, 1972).

For the calibration of the system for use as a moisture meter, three lint samples were taken from each of the three chambers on four separate days, placed in cans, and electrical measurements were made with the experimental equipment, using the acrylic container. For each of these 36 samples, five 1 g subsamples were taken and measured four times in the electronic meter. This procedure resulted in 36 oven determinations of the MC and a total of 720 readings of the current through lint.

THREE SAMPLE HOLDER MATERIALS

Several test samples were taken from the chambers maintained at different relative humidities on four different days and placed in sealed metal cans. Three or four separate 1 g subsamples were taken from each can and placed in each of the three sample holders, resulting in 168 observations with 56 observations for each sample holder material. These data were then used to predict the oven–based MC determined from a 20 g sample from the same can (Shepherd, 1972).

EFFECT OF SAMPLE DENSITY

Samples of lint of varying weights, which had been preconditioned in a chamber of constant relative humidity and temperature, were placed in the PTFE sample holder, compressed to 1 cm³, and a current measurement was made. Initially, 46 subsamples at each of the weights of 0.8, 0.9, 1.0, 1.1, and 1.2 g were measured, resulting in 230 observations at five densities. Next, a set of 60 observations with subsamples weighing 0.4, 0.6, 0.8, 1.0, and 1.2 g were added to the data set. Later, a set of 75 observations with subsamples weighing 0.4, 0.6, 1.0, 1.2, and 1.4 g were added to the data set. This data set had 365 observations with density in the range from 0.4 to 1.4 g/cm³.

RESULTS

CALIBRATION CHECK USING FIXED RESISTORS

The digital output of the A/D converter that was read 0.7 s after sample compression was fit to the log of the resistance using the SAS procedure GLM (SAS, 1991). Initial testing of the system included resistors as high as 3.0 TΩ but some nonlinearity was detected above 100 GΩ. Cotton resistances above 100 GΩ were not expected, so further work above this value was not done. The resulting relationship was:

\[ \ln(R) = 34.92 - 4.638V \]  

where

- \( R \) = calibration resistance
- \( V \) = voltage output from the I/V converter.

The resulting \( R^2 \) was 0.999997 and the root residual mean square was 0.024, showing that the system was able to measure the fixed resistors accurately. The units for the root residual mean square relating to equation 2 are the same as those of the dependant variable of the equation, \( \ln(\Omega) \).

Equation 2 was used to predict the resistance from the data collected on the 22 check dates. The natural logarithm of the resistances varied from 12.6 to 26.4, and the root mean square difference between the predicted and observed was 0.026. The combination of all the resistor–based data resulted in 264 observations. The natural logarithm of the resistance was predicted based on the voltage output of the I/V converter.
The resulting relationship was not significantly different from equation 2, with $R^2 = 0.99995$ and root mean square residual of 0.028. Based on these data, it was concluded that the instrument could be used to measure the resistance of fixed resistors in the range $300 \, \text{k}\Omega$ to $100 \, \text{G}\Omega$ over the time period of the study.

**Calibration of Sample Current Compared to Oven Moisture Content**

There were 36 oven MC determinations in this data set, each corresponding to 20 electronic readings taken 0.7 s after sample compression measured with 12 VDC excitation. The 20 electronic readings were averaged and the means used to predict the oven MC data using the SAS procedure GLM (SAS, 1991). The reference MC was between 4.1% and 8.7% w.b. The relationship between the measured voltage from the I/V converter and the reference MC was:

$$\text{PMC} = -4.3 + 3.26V$$  \hspace{1cm} (3)

where

- $\text{PMC}$ = predicted MC (% w.b.)
- $V$ = measured voltage (V) from the I/V converter.

The $R^2$ for this fit was 0.985 and the root mean square residual was 0.20%. This magnitude of error is in the range expected in the reference MC (Shepherd, 1972), which supports the conclusion that the system was able to accurately measure lint MC over the range tested. Figure 3 shows the MC of the 36 samples as measured by the oven method compared to the mean of the resistance predicted from equation 2 and MC predicted from equation 3. Based on equations 2 and 3, the samples at 4.1% MC had a resistance of 9.1 G$\Omega$ and the samples at 8.7% had a resistance of 13.0 M$\Omega$. These resistances were well within the design capabilities of the measurement system.

**Three Sample Holder Materials**

The three sets of data collected with the three types of sample holders 0.7 s after sample compression were used to predict the same set of reference MC with the SAS procedure GLM. When three separate prediction equations were used, the standard error was 0.25% for the acrylic holder, 0.18% for the PTFE holder, and 0.22% for the UHMWPE holder. When only one equation was used for all three data sets, the root mean square error was 0.22%. When these root mean square errors were compared statistically, the F statistic was not significant; therefore, there was no reason to use separate equations. The resulting relationship was:

$$\text{PMC} = -4.0 + 3.20V$$  \hspace{1cm} (4)

This equation predicted the same MC as equation 3 to within 0.16% over the range of calibration (3.7% to 8.7%). It was concluded that the choice of material among these three should be based on factors other than electrical performance, including price, structural stability, and temperature considerations.

**Effect of Sample Density**

A linear model, with three parameters, was used to predict the measured MC based on the voltages measured 0.7 s after sample compression with 12 VDC excitation and the sample density, in g/cm$^3$, producing a residual root mean square of 0.29%. When a model exponential in density was fit to the data, the residual root mean square was reduced to 0.26%. The resulting model, using four parameters, was:

$$\text{PMC} = -4.64 + 3.31V + 4.3e^{(-2.7\rho)}$$  \hspace{1cm} (5)

where $\rho$ is the sample mass density (g/cm$^3$). Because the residual root mean square was lower for this model and residual analysis provided no evidence that the model should be rejected, it was used in further analysis. Because the residual root mean square using equation 5 was 0.26% and the difference in $\text{PMC}$ predicted by equations 3 and 5 differed by no more than 0.09% over the range of calibration when a density of 1.0 g/cm$^3$ was entered into equation 5, the two equations were considered to not be significantly different.

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Figure 3. Mean of sample resistances measured 0.7 s after compression with excitation at 12 VDC and moisture content predicted with equation 3 compared to moisture content determined by the oven method of 36 cotton samples.
The sample density had a measurable and significant effect on the readings. The effect of uncontrolled variations in density on the predicted MC would be expected to be proportional to the partial derivative of equation 5 with respect to density:

$$\frac{\partial P_{MC}}{\partial \rho} = -11.6e^{(-2.7\rho)}$$ (6)

Values of density within the range of the study were entered into the non-linear equation 6. Based on this equation, the effect of variations in sample density, within the range of density covered by the data, was calculated. These variations would be expected to be about 5 times greater at densities of 0.4 g/cm$^3$ than at densities at 1.0 g/cm$^3$. Likewise the variations would be expected to be about 3 times greater at 1.0 g/cm$^3$ than at 1.4 g/cm$^3$. As the density of the lint sample in a sensing device increases, the effect of variations in density on $P_{MC}$ decreases. However, the variation of $P_{MC}$ due to uncontrolled variation in density decreases exponentially as the density is increased. At a density of 1.8 g/cm$^3$, the expected variation in $P_{MC}$ would be 0.09 times the variation in density. For a variation in density of 1.0 g/cm$^3$, the variation in $P_{MC}$ would be less than half the root mean square residual for $P_{MC}$ observed with equation 3. So 1.8 g/cm$^3$ would be a reasonable maximum design density. Automated resistance-type moisture meters must press the cotton sample against electrodes. These meters should be designed with attention to the density of the sample during the measurement. The density should be repeatable between calibration and field measurements, and uniform density across the area of all electrodes would also improve the quality of the resistance-based MC measurement.

**CONCLUSION**

A laboratory device that could be used to measure and automatically record the current through a cotton lint sample was constructed, calibrated, and used. Data were collected 0.7 s after sample compression using an electrical excitation of 12 VDC. The device produced repeatable data when the current through fixed resistors was measured instead of the current through lint. When the device was calibrated for use in measuring lint MC over the range from 4.1% to 8.7% (w.b.), the standard error was 0.20%. It was concluded that the device could be used to measure the MC of cotton samples. When sample holders made of three different types of plastic were used, there was no significant difference in the lint resistance. The choice of material among the three tested should be based on factors other than electrical performance, including price, structural stability, and temperature. The sample density was found to affect the MC readings in a logarithmic way, with considerably less effect at densities around 1.4 g/cm$^3$ (the maximum density in the data set) than at 0.4 g/cm$^3$ (the minimum density in the data set), so the highest practical density should be used. However, variation in predicted MC at densities above 1.8 g/cm$^3$ would not be significant compared to other sources of variation.

**REFERENCES**


