INVESTIGATONS INTO THE PREDICTION OF CORE BULK USING OFDA INSTRUMENTS

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The compressibility of a mass of unprocessed wool fibres, termed bulk, is positively related to yarn bulk and the wear resistance and appearance retention of carpets produced from that fibre. As wool bulk is positively related to the dimensional measurements of fibre diameter and fibre curvature it is possible to predict wool bulk from measurements of these characteristics. A series of trials have shown the best predictor (R^2 = 85%) of core bulk was a model containing $\log_e$ transformed measurements of mean fibre diameter, mean fibre curvature and small blob percentage derived from an OFDA100 instrument. If a measurement were required in the field, the best predictor (R^2 = 84%) of core bulk was a model containing $\log_e$ transformed measurements of mean fibre diameter, mean fibre curvature and small blob percentage derived from an OFDA2000 instrument where the staple was restrained in a wire frame. A number of simpler models were capable of producing good prediction ($R^2 > 80\%$) using either laboratory or field measurements. The age of the measured sample did not significantly affect its measured core bulk while an assessment of crimp form, as reflected by the degree of lustre in intact greasy staples, did not improve the prediction model.

Wool bulk is a measure of the compressibility of an assembly of fibres which is defined as the specific volume of the fibre assembly in cubic centimetres per gram when under a pressure of 10 g/cm² after a defined preparation history and defined measurement conditions. The bulk of a wool sample taken with a core tube (internal diameter approximately 18 mm) is termed core bulk. Bulk is positively related to yarn bulk (*1*) and the end-product performance of many wool products, particularly those associated with the insulating capacity of knitted garments and the wear resistance and appearance retention of carpets (*2*). The procedure to measure core bulk using an auto-bulkometer is described by a standard test method (*3*) developed for use in a laboratory. As such it is relatively expensive, requires a significant sample size, and is unsuited for routine use under field conditions involving large numbers of individual sheep, as may be involved in a breeding programme to improve their wool bulk (*4*).

Free wool fibres have a three-dimensional curvilinear form (*5*) with theoretical studies showing that the compressional properties of a fibre mass are a function of fibre diameter, fibre curvature and torsion (*6*). Torsion represents the third dimension of fibre crimp. A comprehensive series of trials using an OFDA100 instrument showed that approximately 70% of the variation in the bulk of wool of different types and from sheep of different ages could be explained by the simultaneous measurements of mean fibre diameter and mean fibre curvature (*7-11*). A series of multiple linear regression equations were developed by these and other authors as a low-cost method to predict core bulk from measurements of mean fibre diameter and mean fibre curvature (*11-13*). The two predictor variables were included in the

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model as either multiplicative (*12*) or additive (*11, 13*) effects. The OFDA2000 was subsequently developed for use in the field to measure fibre diameter and fibre curvature whilst scanning “teased out” staples of greasy wool, rather than scanning scoured, conditioned snippets as specified for the OFDA100.

Recent work using the OFDA class of instruments suggests that these instruments are inherently accurate and precise in the measurement of fibre curvature itself (*14*) although the method of scouring can impact on the degree of curvature exhibited by the sample (*10,15,16*). Round-trials carried out with OFDA2000 instruments confirmed that the reproducibility of curvature measurements on greasy wool staples is very close to that achieved with graticules (*17*). There are no published data on the effect of different crimp forms and different methods of fibre restraint on the precision of measuring fibre curvature of individual fleeces in relation to using the measurement to predicted core bulk.

This paper reports the results of investigations to identify the most appropriate methodology and model to minimise the residual error associated with predicting core bulk of individual fleeces from measurements obtained using an OFDA instrument. Specific aspects of the methodology that were investigated were assessing the effect of storage on compressibility, the effect of crimp form as reflected by lustre and the degree of restraint imposed on loose fibre when presented to the OFDA instrument for scanning.

General experimental procedures

Wool measurements. Core bulk was measured using a representative sub-sample of approximately 15 g drawn from the greasy sample. The sub-sample was cut into approximately 20 mm lengths with an industrial guillotine to simulate a cored sample. Each chopped sample was aqueous scoured, dried, carded with a WRONZ Corecard machine and the core bulk measured with a WRONZ Auto-Bulkometer according to the New Zealand standard test method for core bulk (*3*).

Mean fibre diameter and mean fibre curvature were measured by both the OFDA100 and OFDA2000 instruments. Snippets measured in the OFDA100 instrument were taken by mini-core (2 mm internal diameter tubes) from the scoured and dried sub-sample used for measurement of core bulk. Specimens measured using an ODFA2000 comprised up to four micro-staples drawn from the original greasy sample. They were solvent scoured and the teased-out staples restrained in different devices for presentation to the OFDA2000 instrument. The complete range of parameters measured by each instrument was recorded for each sample.

Statistical analysis. Balanced data sets were analysed by linear regression, fitting terms as appropriate for each trial. The proportion of variation in core bulk explained by the various models or imposed treatments was assessed by multiple regression using GenStat (*18*).

Trial Methodology and Results

Length of storage effect (Trial 1). During the course of work developing the relationships reported by Sumner and Upsdell (*11*) using an OFDA100 instrument, wool samples collected between December 1995 and September 2000 were measured and the residue retained. Whilst investigating the accuracy of using different models to predict core bulk, it was appropriate to evaluate the stability of core bulk measurements when samples or standards have been stored for extended periods in a greasy state. Accordingly the core bulk of a subset of 30 midside fleece samples that were the retained residues from the measurements reported by Sumner and Upsdell (*11*), and that covered the range in core bulk values, were re-measured in June 2004. The measurements were carried out by the same laboratory that had made the original measurements.

The mean difference in core bulk between the initial and repeat measurements, together with the 95% confidence limits of the means, are plotted against the storage time between measurements in Figure 1.

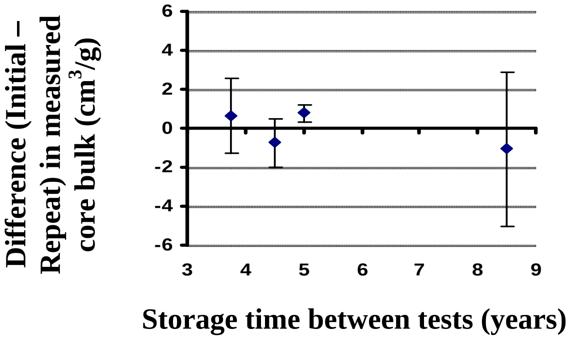

Figure 1. Mean difference (initial - repeat) in core bulk (cm^3/g) of samples re-measured after an extended period of storage. Vertical bars represent 95% confidence intervals.

The overall difference in core bulk measurements averaged over the 30 results was 0.3 cm^3/g, which was not significantly different from 0.0. The variability of the differences suggested an average precision of ± 2.4 cm^3/g, which is slightly in excess of the expected precision of ± 1.9 cm^3/g at an average level of 27 cm^3/g. This estimate includes an additional component of variance due to sampling as well as the variable storage period. There was thus no evidence that there had been a change in measured core bulk over a period of up to nearly 9 years.

Measurement instrument, method of fibre restraint and form of prediction equation (Trial 2). This trial was initially established to evaluate whether there were any potential differences in predicted core bulk associated with crimp form (planar or helical fibre crimp). Hence a range of wool samples were selected to represent a wide variation in staple and fibre crimp form. A total of 380 wool samples taken from the midside region of the body of 180 yearling ewes, 150 yearling rams and 50 samples from sheep of unrecorded sex were available to use in the trial. The sampling strata involved six sets of 30 samples from Poll Dorset, Perendale and GrowBulk, yearling ewes and rams. There were also two sets of 30 samples from a flock of Romney and another flock of GrowBulk yearling ewes. All the yearling sheep had been shorn as lambs in the early summer and were fleece sampled the following spring before hogget shearing. In addition four sets of wool samples from young, previously shorn, Merino sheep were available. These included 30 samples from a flock of fine “soft rolling skin” (SRS) Merino ewes and 30 samples from rams in the same flock, 30 samples from a flock of fine type Merino yearling rams and 50 medium type Merino samples from young sheep of unrecorded sex.

Crimp form was modified by subjecting each sample to three forms of fibre restraint while fibre diameter and fibre curvature were being measured. Maximum constraint was achieved by using an ODFA100 to measure short snippets pressed under glass. Medium constraint was achieved by using an OFDA2000 to measure teased staples held in a heavy grade fibreglass (polyester) slide with milled slots at 5 mm centres. Minimum constraint was achieved by using an OFDA2000 to measure teased staples held in a wire frame supporting the fibres at 10 mm centres with the top and bottom set offset by 5 mm to give alternating "up" and "down" support. This degree of support was considered the minimum constraint consistent with satisfactory instrument performance.

Mean fibre diameter and mean fibre curvature together consistently explained the greatest proportion of the variation in core bulk, with the small proportion of variation explained by the proportional area of small blobs along the fibres (*19*) also attaining statistical significance. The relative accuracy of prediction was evaluated for a structured series of models of increasing complexity, developed to predict core bulk from the measurements that explained the greatest proportion of the variation in core bulk.

Previously reported prediction models (*11*,*12*) used core bulk as the predictor variable with additive errors. This leads to a constant additive error of prediction with a larger percentage error of prediction at low values and a smaller percentage error at high values. Users of the predicted core bulk values may prefer a constant percentage error in prediction. To address this distortion in the error of prediction two forms of predictive model were developed - one set predicted core bulk and the other set predicted $\log_e$ core bulk. Values from the second set of models would, if used in the field, be back-transformed for presentation.

The nested series of models that were evaluated are shown below, where CB = core bulk, FD = mean fibre diameter, FC = mean fibre curvature and small blob = the proportional area of small blobs along the fibres.

Model form used by Sumner and Upsdell (2001).

$$CB = a + b\ FD + c\ FC \qquad \text{Model 1}$$

Recognising there is a significant curvilinear relationship between core bulk and mean fibre curvature (Sumner and Upsdell, 2001):

$$CB = a + b\ FD + c\ FC + d\ FC^2 \qquad \text{Model 2}$$

Including the "small blob" effect:

$$CB = a + b\ FD + c\ FC + d\ FC^2 + e\ \text{Small blob} \qquad \text{Model 3}$$

Model form used by Baxter (1996):

$$CB = a + b\ FD\ FC \qquad \text{Model 4}$$

Dropping the constant term to align with a log transformation model:

$$CB = b\ FD\ FC \qquad \text{Model 5}$$

Log_e transformation of Model 5:

$$\text{Log}_e\ CB = a + \text{Log}_e\ FD + \text{Log}_e\ FC \qquad \text{Model 6}$$

Allowing the coefficients of $\mathrm{Log_e}$ FD and $\mathrm{Log_e}$ FC to be different from 1:

$\mathrm{Log_e}\ CB = a + b\ \mathrm{Log_e}\ FD + c\ \mathrm{Log_e}\ FC$ Model 7

Recognising there is a significant curvilinear relationship between core bulk and mean fibre curvature (Sumner and Upsdell, 2001):

$\mathrm{Log_e}\ CB = a + b\ \mathrm{Log_e}\ FD + c\ \mathrm{Log_e}\ FC + d\ (\mathrm{Log_e}\ FC)^2$ Model 8

Including the "small blob" effect:

$\mathrm{Log_e}\ CB = a + b\ \mathrm{Log_e}\ FD + c\ \mathrm{Log_e}\ FC + d\ (\mathrm{Log_e}\ FC)^2 + e\ \mathrm{Log_e}\ \text{Small blob}$ Model 9

The summary statistics for Models 1 to 5 for each of the three forms of restraint are given in Table I with the summary statistics for Models 6 to 9 for each of the three forms of restraint given in Table II. The residual error of the untransformed data in Table I is measured in cm^3/g while the residual error of the $\log_e$ transformed data in Table II is measured as a %. While the proportion of explained variation (R^2 value) in each table is expressed as a %, the variance to be explained has changed on account of the applied data transformation. Thus Models in different tables cannot be directly compared statistically. Models 5 and 6 were included to complete a logical series of transformational steps. Each has a large residual error and explains an insignificant proportion of the variation in measured core bulk. As such neither model is considered further.

Table I. Summary statistics of best fitting equations for Models 1 to 5.

Model	OFDA100		OFDA2000			
			Polyester frame		Wire frame	
	Residual error (cm^3/g)	Explained variation (R^2) (%)	Residual error (cm^3/g)	Explained variation (R^2) (%)	Residual error (cm^3/g)	Explained variation (R^2) (%)
1 CB = a + b FD + c FC	1.68	82.5	1.81	79.7	1.77	80.5
2 CB = a + b FD + c FC + d FC^2	1.60^{***}	84.2	1.69^{***}	82.2	1.68^{***}	82.6
3 CB = a + b FD + c FC + d FC^2 + Small blob	1.56^{***}	84.9	1.68^{*}	82.3	1.68	82.4
4 CB = a + b FD FC	1.68	82.5	1.90	77.6	1.86	78.5
5 CB = b FD FC	3.20^{***}	36.5	4.20^{***}	0.0	4.02^{***}	0.0

Asterisks indicate the level of significance of the change in residual error from the previous model in the set (* = $P<0.05$, ** = $P<0.01$ and *** = $P<0.001$).

Of the valid core bulk prediction models, Models 1 and 7 were the "worst" predictors with the highest residual error within the two sets of models regardless of the method of fibre restraint and Models 3 and 9 were the "best" predictors with the lowest residual error within the two sets of models regardless of the method of fibre restraint. While the reduction in residual error is relatively small with the addition of each new term in the respective models for each form of restraint, the change in residual error is significant for each change except for progressing from Model 2 to Model 3 for the OFDA2000 when the sample is held in a wire frame. The significance of the change in residual error is a reflection of the large number of samples and the wide range in the predictive variates.

Table II. Summary statistics of best fitting equations for Models 6 to 9.

Model	OFDA100		OFDA2000			
			Polyester frame		Wire frame	
	Residual error (%)	Explained variation (R^2) (%)	Residual error (%)	Explained variation (R^2) (%)	Residual error (%)	Explained variation (R^2) (%)
6 $\log_e CB = a + \log_e FD + \log_e FC$	12.68	36.9	18.29	0.0	17.19	0.0
7 $\log_e CB = a + b \log_e FD + c \log_e FC$	6.24^{***}	83.8	6.59^{***}	81.9	6.60^{***}	81.8
8 $\log_e CB = a + b \log_e FD + c \log_e FC + d (\log_e FC)^2$	6.03^{***}	84.8	6.24^{***}	83.7	6.27^{***}	83.6
9 $\log_e CB = a + b \log_e FD + c \log_e FC + d (\log_e FC)^2 + \log_e \text{Small blob}$	5.97^{***}	85.1	6.18^{***}	84.0	6.13^{***}	84.3

Asterisks indicate the level of significance of the change in residual error from the previous model in the set (* = $P<0.05$, ** = $P<0.01$ and *** = $P<0.001$).

Plots of the relationships for Models 1, 3, 7 and 9 for each of the methods of restraint are given in Figure 2. These plots visually indicate the differences between the valid models and the three forms of fibre restraint. Measurements using the OFDA100 instrument, where snippets are restrained under glass, had a lower residual error than when the fibres were subjected to medium or minimum restraint when viewed by the OFDA2000 instrument for both Models 3 and 9. Since users require a small error when the reading is small and can tolerate a larger error when the reading is larger, Model 9 which minimises the percentage error is preferable. In addition it uses a modification of the multiplicative model indicated by theoretical considerations (*6*).

Lustre effect (Trial 3). This investigation was carried out to assess whether lustre, as assessed by an experienced person, could help explain anomalies between measured and predicted core bulk. Specifically, was subjectively-assessed lustre sufficiently related to differences in crimp form, (planar vs helical) to influence the residual error associated with predicted core bulk?

A total of 90 midside fleece samples from Poll Dorset, Perendale and Romney ewe hoggets shorn as lambs in the early summer and fleece sampled in the following spring before hogget shearing (Trial 1) were visually assessed for degree of lustre on an arbitrary scale of 1 (High lustre) to 5 (Low lustre). The range in degree of assessed lustre was set to encompass the range in lustre which occurs naturally across these types of wool.

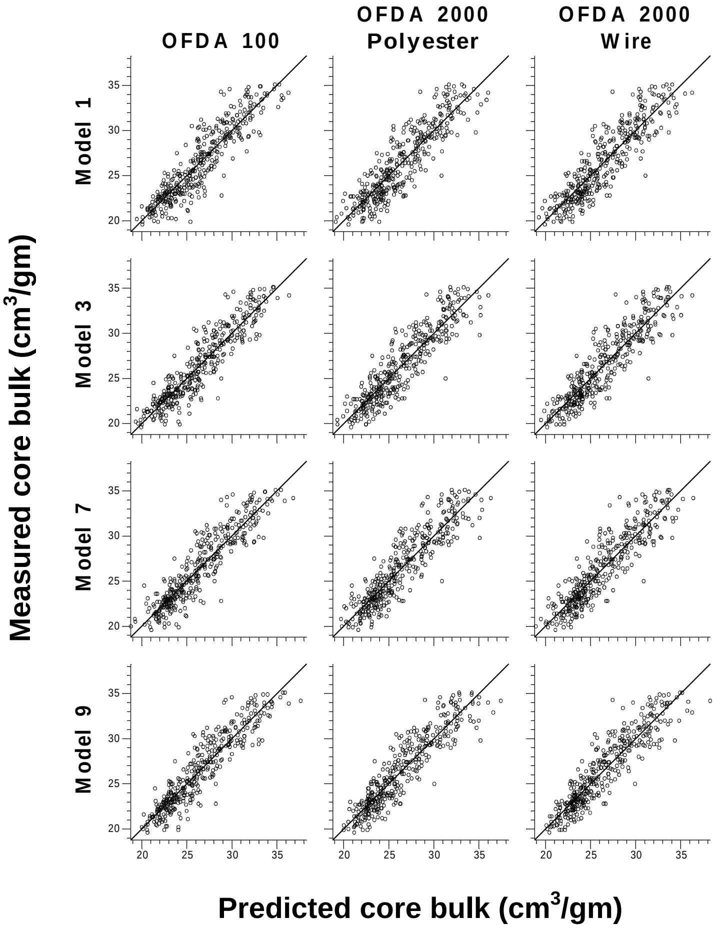

Figure 2. A “trellis” plot of measured core bulk against predicted core bulk for each of the three forms of restraint where core bulk is predicted by the “worst” and “best” models for untransformed (Model 1 and Model 3 respectively) and $\log_e$ transformed data (Model 7 and Model 9 respectively).

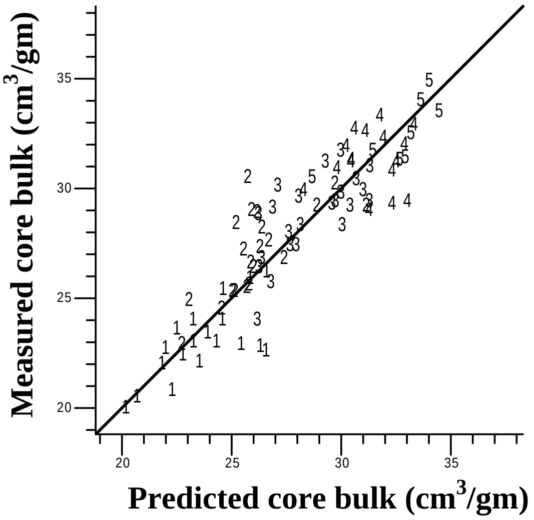

Figure 3. Plot of measured core bulk against predicted core bulk for the samples subjectively assessed for lustre grade with the lustre grade indicated for each sample. 1 = High lustre to 5 = Low lustre.

There was a significant positive relationship between measured core bulk and assessed lustre grade (R^2 = 71%) which can be explained by the differences in fibre diameter, fibre curvature and the area of the small blobs. The residuals from the OFDA100 data, using Model 9, were not significantly correlated with assessed lustre grade ($P>0.05$). A plot of measured core bulk against core bulk with the lustre grade of each sample marked on the graph for the samples assessed for lustre grade is given in Figure 3. Assessed lustre, as an indication of crimp form expressed within staples of greasy wool, did not improve the model.

Discussion

Core bulk has had a relative economic value of between 4 and 14 NZ cents per unit increase in bulk (cm^3/g) per kg of clean wool (*20*) since the recognition of wool bulk as trait of importance in carpet manufacture (*21*). The data on which these values are based is limited, as relatively few lines of wool are objectively measured on account of the cost of the standard test. Notwithstanding, lines of sheep have been developed with an increased wool bulk and a minimal reduction in fleece weight (*22*). However, because of the low relative economic value of wool bulk, the long-term success of such an approach is dependent on a low-cost method of measuring core bulk of individual fleeces. The prediction of core bulk using an appropriate model, incorporating data collected as a routine procedure, is very effective for calculating the mean bulk of a blended line of wool. However, the inherent imprecision associated with predicting the bulk of individual fleeces could have serious economic consequences when ranking individual ewes, and particularly individual rams, for breeding and sale on the basis of their predicted bulk (see Marler and Baxter (*23)* for a discussion of the implications of measurement imprecision on selection). Uptake of this approach by industry is dependent on the associated residual error being as small as practically possible.

Baxter (*12*) initially proposed the model:

$$CB = 13.5 + 0.009\ (FD\ FC)$$

to predict core bulk using fibre diameter and curvature measurements determined with an OFDA100 instrument. Subsequently Baxter, in an unreported investigation, using 180 midside fleece samples from nine flocks of unspecified genotypes encompassing a range in core bulk from 18 to 33 cm^3/g and mean fibre diameter from 16 to 50 µm, measured the mean fibre diameter and mean fibre curvature of each sample in duplicate with an OFDA2000 instrument. The “best fit” prediction equation determined by least squares regression was (Baxter, unpublished data):

$$CB = 14.4 + 0.0076\ (FD\ FC)$$

When this equation was applied to the data set used in calibration, the standard error of the regression of measured core bulk against predicted core bulk was ± 1.55 cm^3/g. The precision of the standard method of measuring core bulk averages approximately ± 2 cm^3/g over the measured range. Assuming that the measurement of core bulk and the predictive measurements can be considered independent, the overall precision (95% confidence limits) of the predictive method was estimated by summation of variances, with allowance for duplication of the OFDA 2000 measurements, to be ± 2.4 cm^3/g for duplicate measurements and ± 3.3 cm^3/g for a single measurement.

Earlier studies (*24-26*) have shown that the elapsed time in months, or even years, since keratinisation within the wool follicle may affect the stress relaxation at that point of the fibre. This so called “chemical aging” may affect bending rigidity and hence the bulk properties of fibre assemblies measured at different times. No effect of practical significance was evident for the samples measured in this study that would be sufficient to impact on the robustness of a bulk prediction equation for wools of different ages or over time for equivalent experimental conditions.

While the reduction in residual error resulting from the introduction of additional terms into the predictive models associated with each of the forms of fibre restraint was small, the effect was always significant, except for the introduction of a small blob term (Model 3) for fibres presented to an OFDA2000 restrained in a wire frame. In comparing the three methods of fibre restraint the scanning of short snippets compressed between sheets of glass appears to best take account of inherent fibre torsion resulting in the lowest residual error regardless of the predictive model used.

The physical significance of the small blob parameter can only be speculated upon. There is some evidence from work carried out on the differentiation of fibre species (B.P. Baxter, unpublished data.), that small blob may be related to fibre surface roughness, and if this were the case, then it is feasible that increased small blobs may relate to increased surface roughness and thereby increased fibre to fibre friction and as a result increased resistance to compression in a random assemblage of fibres.

Conclusions

Overall the most precise procedure to predict core bulk was to use a model involving $\log_e$ transformed data (Model 9) derived from an OFDA100. If the data is required to be collected and used in the field, the same model (Model 9) for data derived from an OFDA2000 with the staples held in a wire frame will provide the best estimate of core bulk. This results in only a very small increase in residual standard error from 6.0% to 6.1% when compared to use of the OFDA100. However, some of the simpler models were also capable of producing relatively good prediction ($R^2 > 80\%$) using either laboratory or field measurements.

The overall precision of predicting core bulk using these techniques is very similar to that of measuring core bulk by the standard test method. Further evaluatory work is required to indicate whether measured or predicted core bulk provides the better indicator of processing and end-product performance.

The form of fibre crimp, as it may relate to the assessed lustre of intact greasy staples, did not impact on the accuracy of prediction of core bulk, nor did the age of the sample.

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