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Measurement of Staple Crimp Frequency Part 1: Manual Measurements using the Crimp Gauge

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SUMMARY

The objectives of this paper were to provide a set of reference staples with Crimp Frequency (CF) measurements from a standardised manual method that could be compared to the results of a crimp meter currently under development at AWTA Ltd^{11, 12}; and, to investigate sources of variability in the manual measurement of staple CF.

Twenty-seven sale lot grab samples representing broad, medium and fine wool types were obtained from the three wool-selling regions of Australia. Six operators were trained to undertake the measurement of staple CF on approximately 60 staples from each sale lot.

The trial incorporated two stages viz, a proficiency trial designed to evaluate the training of operators in manual staple CF measurement and a staple CF measurement trial.

The grand mean staple CF, the total observed variance and the average 95% Confidence Interval were 4.2 crimps/cm, $0.55 \text{ (crimps/cm)}^2$ and $\pm 1.4 \text{ crimps/cm}$ respectively. The staple CF, the observed total variance and the precision estimates for a set of 27 sale lots can be used to assess the performance of a crimp meter

This paper has proposed a model to estimate the sources of variation in the manual measurement of staple CF.

Source of Variation	Variance (crimp/cm) ²	Percentage of Total
Between-staple-within lot	0.55	43.7
Within-operator	0.29	23.0
Within-staple	0.22	17.5
Between-operator	0.20	15.9
Total	1.26	100.0

Variance estimates have been calculated for the sources of variation. When one considers that 60 staples are usually measured on ATLAS, the within and between operator variances become the major contributors to the total observed variance representing approximately 62.8 % and 11.5% of the total observed variance.

The data presented demonstrate that, although time consuming, the manual method reported provides a relatively precise measure of staple CF on staples prepared for the measurement of Staple Length and Staple Strength.

INTRODUCTION

It is well known in the wool industry^{2,3,4} that the quality of greasy wool has been associated with its Crimp Frequency (CF). The Bradford Quality Count was an indicator of the processing quality of wool. Duerden in 1929 proposed a measurement technique that related the Bradford Quality Count to staple CF¹. This method measured staple CF in units of crimp per inch.

Although today Fibre Diameter measurement has replaced the Bradford Quality Count and the Duerden scale, some buyers still use a subjective appraisal of CF when purchasing wool.

Previous studies^{5,6,7} on staple CF have shown that when other raw wool parameters such as Mean Fibre Diameter, Staple Length and Staple Strength are controlled within narrow limits, low staple CF delivers longer Hauteur and less Noil in top manufacture compared to high staple CF. These studies have shown the potential usefulness to processors of quantifying the staple CF of wools.

Subjective measurements of staple CF have been made in numerous past studies^{8,9,10}. This paper presents an attempt to standardise the manual measurement of staple CF utilising operators and the CSIRO crimp gauge.

The primary objective of this work was to provide a set of reference staples and associated CF results from a standardised manual method that could be compared to a crimp meter currently under development at AWTA Ltd^{11,12}.

The secondary objective was to investigate and quantify sources of variability in the manual measurement of staple CF using a Crimp Gauge, including, within staple variability, within and between operator variability and the variability between staples within a lot.

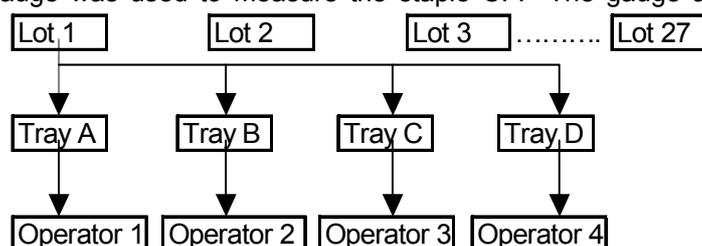
MATERIAL AND METHOD

Materials

The trial design required the selection of sale lots with a large range in visually assessed CF. Therefore, a set of 27 sale-lot grab samples representing broad, medium and fine CF wool types was obtained from the three wool-selling regions of Australia. Tufts were sampled from each grab sample and four trays of staples were then prepared from each lot using 4 staple preparation operators in accordance with IWTO-7-00. Figure 1 illustrates the preparation process.

Figure 1. Staple preparation stages

The CSIRO Crimp Gauge was used to measure the staple CF. The gauge acts as a comparator in



which the successive peaks in the “waves” of crimp in a wool staple are matched to the teeth of the Crimp Gauge. A reading is then made of the number of crimps/cm of the teeth on the gauge. The gauge thus enables an operator to measure staple CF in units of crimps per cm. Figure 2 shows the gauge with two staples: a relatively high CF staple approximately 6 crimps/cm above and a relatively low CF staple approximately 3 crimps/cm below the gauge.

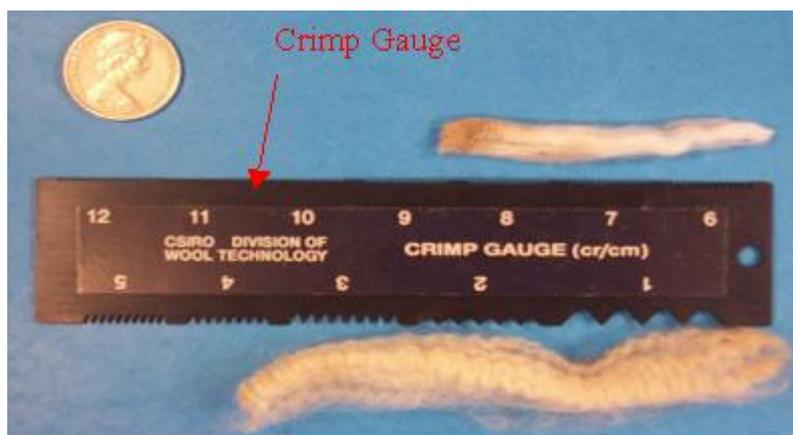


Figure 2. CSRIO Crimp Gauge

Method

Part I: Proficiency Trial

Approximately 20 staples were used as a training set to assist the training of six operators in the use of the Crimp Gauge for the manual measurement of staple CF.

Staple CF was measured at two points along the length of individual staples as illustrated in Figure 3. One measurement was made at the imaginary boundary between the root and middle thirds of the staple (root) and the second measurement was made at the imaginary boundary between the middle and tip thirds of the staple (tip). The average of the two was deemed to be the measured CF of the staple.

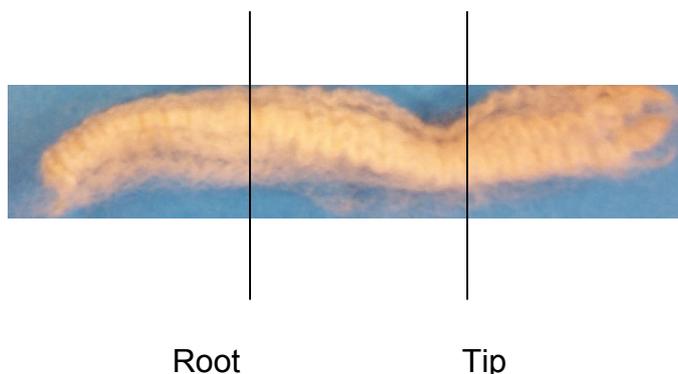


Figure 3. Locations of staple CF measurement on a staple

Another set of approximately 50 staples was used to assess the proficiency of the trained operators. Each of the six operators measured each of the 50 staples twice so that the within-operator variance for staple CF could be estimated.

The set of staples was measured on one day by each of 6 operators. The staples were then randomly rearranged and the operators were asked to remeasure the staples on a second day. The variance between the first and second measurement for each operator was calculated as an estimate of the within-operator variance. The variance between the averaged root and tip measurement was also calculated for each operator individually and then pooled to obtain an estimate of the within-staple variance.

In the cases where the operators were not able to obtain a CF reading due to an unclear wave pattern in the staple, the result for that staple was recorded as “No Result”.

Part II: Measurement of 27 Sale Lots

The six trained operators measured the trays of staples prepared from the 27 sale lots. Two operators each measured a single tray of approximately 15 staples independently and their measurements were recorded. Similarly, other pairs of operators measured the remaining 3 trays from each sale lot.

A pool of operators was used because previous studies^{6,10} indicated that the variability both within and between operators was potentially a large source of variation in measured staple CF.

The staple CF reference value for an individual staple was calculated by combining all data for the staple as detailed in Figure 4.

A comparison of the average reading for a staple by the two operators was used to check the trial data. Where this differed by greater than ± 1.5 crimps/cm, an experienced operator assessed the staple to determine the final staple CF. The re-measured staple CF result was then recorded as the final reference staple CF value for that staple instead of the average of the two operators.

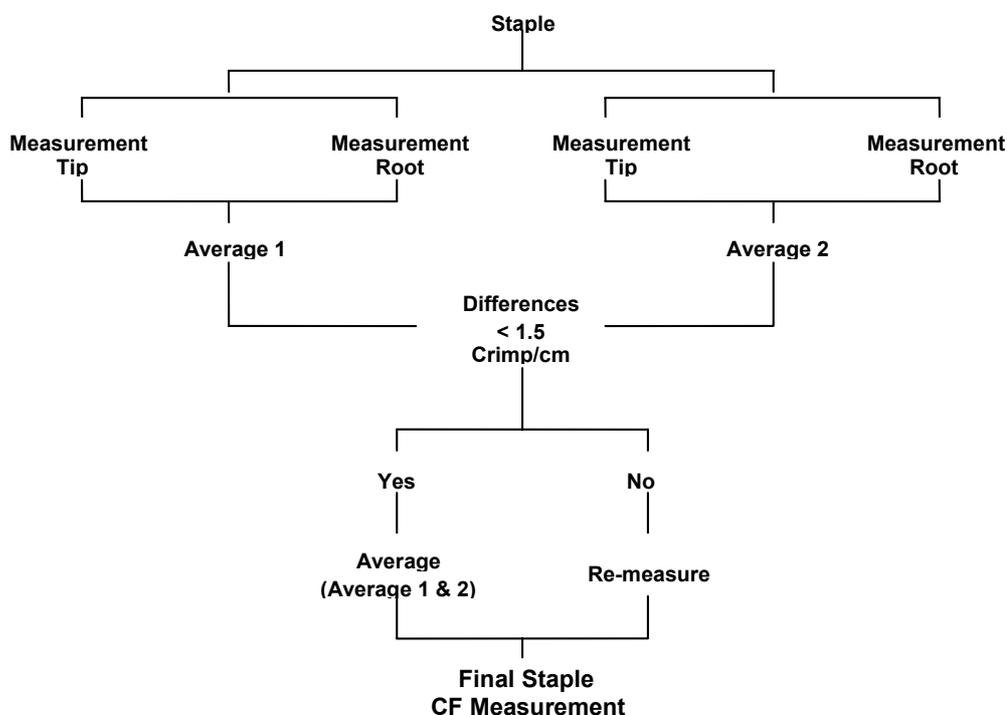


Figure 4. Staple CF measurement process

Data Analysis

The average tip and root CF were calculated together with the average variance between tip and root for each staple in a lot. The variability within and between operators was also investigated in the proficiency trial.

The lot average staple CF and the observed total variance of staple CF for each of the 27 sale lots were calculated from the staples measured within each lot and then used by Semmel¹² for a comparison with a crimp meter. An estimate of the 95% Confidence Interval was also calculated.

For the purpose of calculating the confidence limit of the mean value for a sale lot a variance model was proposed for the trial design. This model was then used to estimate the between-staple-within lot variance and enable the breakdown of the variance components that impact on the precision of the mean

value into percentages of the total observed variance. The model is defined mathematically in Equation 1.

$$\sigma^2_{Total} = \frac{\sigma^2_{sampling}}{N_{staple}} + \frac{\sigma^2_{between-ops}}{N_{ops}} + \frac{\sigma^2_{within-staple}}{N_{position}} + \frac{\sigma^2_{within-ops}}{1} \dots\dots\dots[1]$$

Where:

- σ^2_{total} = the observed total variance in staple CF measurement
- N_{staple} = the number of staples measured for a lot
- $\sigma^2_{sampling}$ = the between-staple-within-lot variance
- $\sigma^2_{between-ops}$ = the variance between operators
- N_{ops} = the number of operators used to measure a lot
- $\sigma^2_{within-staple}$ = the variance in staple CF that exists along a staple (tip+root)
- $N_{position}$ = the number of positions along a staple where the CF measurement was taken
- $\sigma^2_{within-ops}$ = the variance of repeated measurement by an operator for staple CF measurement

RESULTS AND DISCUSSION

WITHIN-OPERATOR VARIANCE

The within-operator variance was estimated for each operator. It was investigated by comparing the first and second set of crimp measurements by each operator in the proficiency trial. Table 1 presents the estimated within-operator variance.

Table 1. The within-operator variances for each operator

Operator	Within-Operator Variance	No Result
1	0.27	19
2	0.14	5
3	0.48	2
4	0.32	1
5	0.13	0
6	0.42	0
Average	0.29	4.5

The estimates of the within-operator variance range from 0.13 to 0.48 and average 0.29. Operator 3 has a larger variance estimate compared to the other operators. This was due to a single outlier that on the first measurement measured 9 crimps/cm and on the second measurement it measured 4 crimps/cm. Operators 2 and 5 were very consistent while operators 1, 4, and 6 had intermediate values for within-operator variability. Operator 1 had significantly more “No Result” recorded compared to the other operators.

Figure 5(a-f) graphically illustrates the relationships between the first and second measurement for each operator.

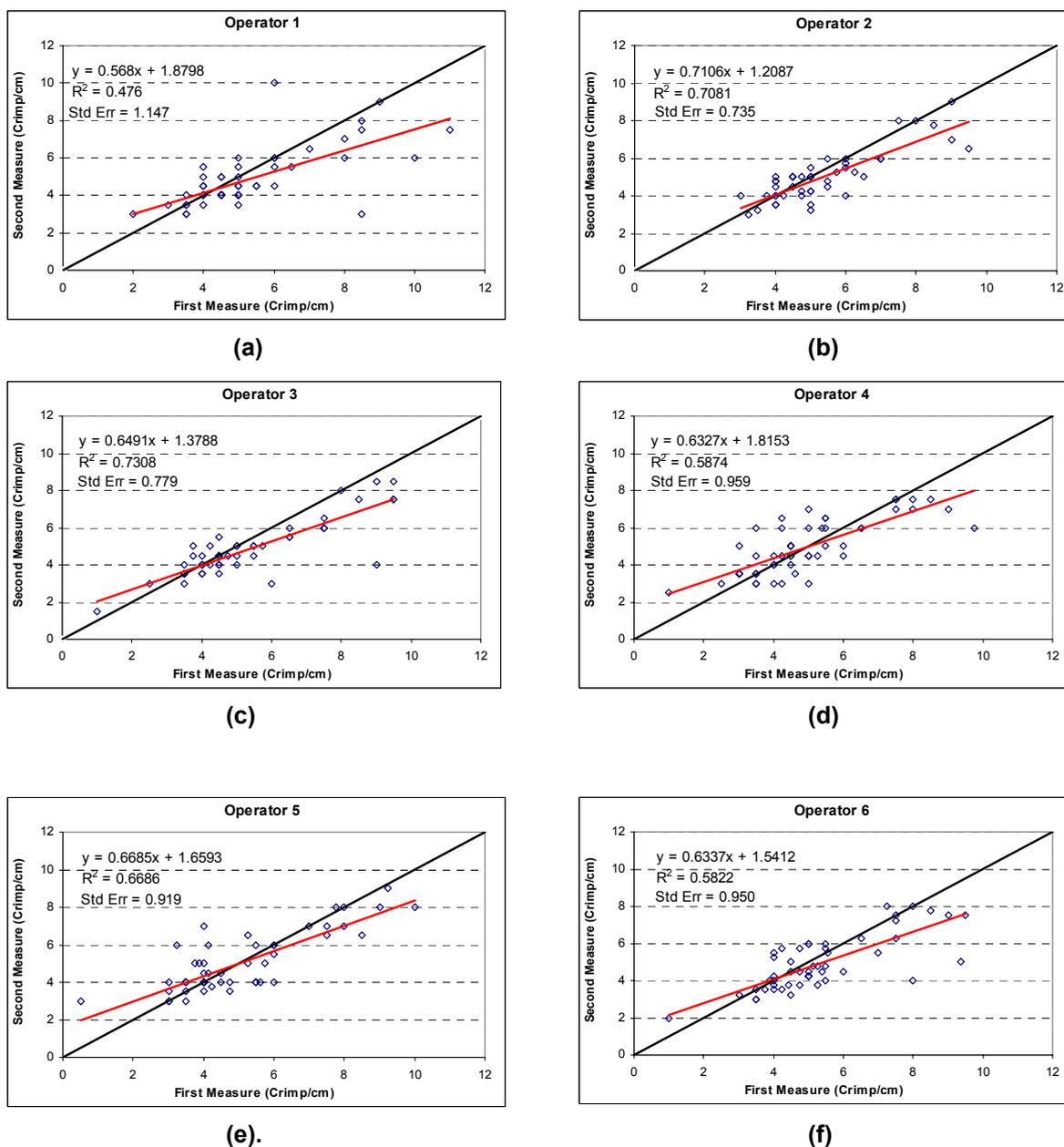


Figure 5. The relationship between the first and second measurement for each operator

Operators 1, 2, 3 and 4 have all registered no-recorded result for staples either for the first or repeat measurement. Operators 5 and 6 were able to obtain a staple CF reading for all of the staples in both the first and repeat measurements. The standard errors of regression in Figures 5(a-f) range from 0.735 to 1.147 crimps/cm.

WITHIN-STAPLE VARIANCE

The analysis performed in this section has had 11% of staples re-measured by an independent operator.

The within-staple variance was estimated by calculating the variation between the tip and root staple CF for each staple. The variance was then pooled for all staples within a lot. The within-staple variance ranged from 0.11(crimps/cm)² to 0.34 (crimps/cm)². The pooled average tip and root staple CF's and the within-staple variance are shown in Table 2 for each of the 27 sale lots.

The grand average tip and root staple CF's were 4.1 crimps/cm and 4.2 crimps/cm and the average within-staple variance was 0.22 crimps/cm.

Table 2. Average tip & root readings and within staple variance for 27 sale lots

Lot	Tip (cm ⁻¹)	Root (cm ⁻¹)	Within-Staple Variance
1	4.4	4.5	0.24
2	5.8	6.0	0.19
3	4.7	4.7	0.33
4	4.5	4.8	0.34
5	4.4	4.6	0.23
6	3.9	4.0	0.22
7	5.4	5.5	0.17
8	3.5	3.6	0.17
9	3.9	4.1	0.23
10	3.9	3.9	0.16
11	2.8	2.7	0.16
12	2.4	2.5	0.14
13	3.8	3.7	0.12
14	6.3	6.5	0.19
15	4.4	4.4	0.19
16	3.1	3.4	0.30
17	1.4	1.5	0.11
18	4.9	4.6	0.24
19	3.9	4.1	0.21
20	3.1	3.2	0.18
21	4	4.4	0.21
22	3.6	3.5	0.30
23	3.4	3.3	0.23
24	5.6	5.9	0.29
25	4.8	5.1	0.34
26	6.1	6.2	0.28
27	2.7	2.9	0.24
Average	4.1	4.2	0.22

Figure 6 depicts graphically the relationship between average staple CF and the within-staple variance for each of the 27 sale lots. An upward trend can be seen, indicating that as staple CF increases the within-staple variance increases.

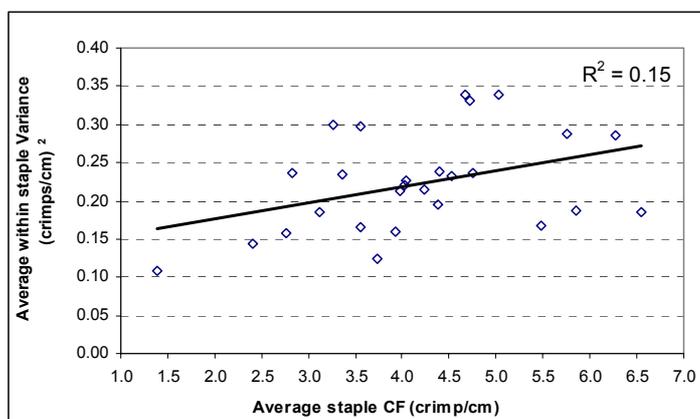


Figure 6. Relationship between Staple CF and Within-staple Variance.

R² is a measure of the percentage variation accounted for by the trend line. Thus a small R² of 0.15 suggests that the relationship between staple CF and within-staple variance is not strong as staple CF accounts for only 15% of the variation in within-staple variance.

BETWEEN-OPERATOR VARIANCE

The observed between-operator variance was estimated by calculating the variation between the staple CF measurement made by the two operators on individual staples. Table 3 shows the variances for the operator pairs that measured the same tray of staples in each lot. The pooled between-operator variance estimate is also reported.

Table 3. Estimated between operator variances in each tray

Lot	Estimated Between-Operator Variance				
	Operator Pair A (Crimp/cm)	Operator Pair B (Crimp/cm)	Operator Pair C (Crimp/cm)	Operator Pair D (Crimp/cm)	Pooled Operator Pair Average (Crimp/cm)
1	0.33	0.12	0.22	0.11	0.20
2	0.20	0.17	0.25	0.66	0.32
3	0.33	0.26	0.21	0.27	0.27
4	0.38	0.20	0.26	0.36	0.30
5	0.32	0.24	0.24	0.33	0.28
6	0.29	0.14	0.18	0.18	0.20
7	0.20	0.39	0.10	0.13	0.20
8	0.27	0.16	0.13	0.22	0.19
9	0.18	0.13	0.14	0.25	0.17
10	0.32	0.29	0.14	0.13	0.22
11	0.18	0.08	0.11	0.14	0.13
12	0.12	0.06	0.11	0.08	0.09
13	0.17	0.11	0.18	0.23	0.17
14	0.45	0.39	0.21	0.20	0.31
15	0.21	0.08	0.18	0.13	0.15
16	0.17	0.14	0.13	0.21	0.16
17	0.02	0.07	0.18	0.02	0.07
18	0.33	0.07	0.14	0.15	0.17
19	0.22	0.21	0.14	0.21	0.19
20	0.27	0.15	0.13	0.04	0.15
21	0.32	0.19	0.20	0.23	0.24
22	0.28	0.20	0.07	0.13	0.17
23	0.20	0.13	0.13	0.20	0.16
24	0.29	0.56	0.13	0.21	0.30
25	0.13	0.18	0.11	0.22	0.16
26	0.13	0.17	0.20	0.26	0.19
27	0.11	0.15	0.13	0.05	0.11
Mean	0.24	0.19	0.16	0.20	0.20

The data summarised in Table 3 show that on average for the 27 sale lots, the between-operator variance was 0.24, 0.19, 0.16 and 0.22 (crimps/cm)² for Pairs A, B, C and D, respectively. The between-operator variance for some lots was much larger than the average value. For example, in lot 14 the between-operator variances, for the 4 operator pairs, were 0.45, 0.39, 0.21 and 0.20 respectively. Lot 14 exhibited a secondary staple crimp wave, or double crimp, at approximately 2 crimps/cm and an over crimp of approximately 6 crimps/cm, and for some staples operators were only recording one of the 2 dominant staple CF's present.

The variance data shown in Table 3 indicate the variability between the measurement of staple CF by two operators for each tray of staples in a lot. The pooled operator paired average variance was 0.20 (crimps/cm)²

The observed between-operator variance for each operator pair is plotted against the average staple CF for the 27 sale lots in Figure 7. The graph demonstrates that as the staple CF increases the variability between operator pairs increases, i.e. the consistency between operators in the measurement of staple CF decreases as the staple CF increases.

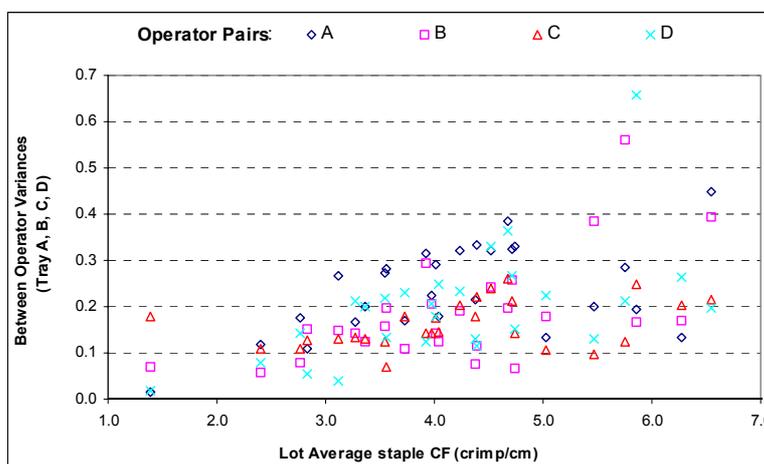


Figure 7. Relationship between Staple CF and the Between-operator Variance

FINAL STAPLE CRIMP FREQUENCY & OBSERVED TOTAL VARIANCE

The final staple CF for a lot and the observed total variance were obtained for a comparison with a crimp meter currently under development at AWTA Ltd.

Table 6 summarises the average staple CF, the observed total variance estimate and the 95% Confidence Interval for each lot. The grand mean staple CF for the 27 sale lots was 4.2 crimp/cm and the observed total variance was 0.55. The average 95% Confidence Interval for the 27 lots was ±1.40 ranging from ±0.88 to ±0.2.73.

Table 6. Summary of Final Staple CF and Observed Total Variance and Precision Estimates

Lot	Staple CF (Crimp/cm)	Observed Total Variance (Crimp/cm) ²	95% CI for Mean Staple CF (N=60) (Crimp/cm)
1	4.4	0.58	1.50
2	5.9	0.99	1.95
3	4.7	0.79	1.75
4	4.7	0.86	1.81
5	4.5	0.42	1.27
6	4.0	0.67	1.61
7	5.5	0.44	1.31
8	3.6	0.29	1.06
9	4.0	0.39	1.23
10	3.9	0.51	1.40
11	2.8	0.26	1.00
12	2.4	0.26	1.00
13	3.7	0.27	1.02
14	6.5	1.94	2.73
15	4.4	0.61	1.54
16	3.3	0.37	1.19
17	1.4	0.20	0.88
18	4.7	0.38	1.21
19	4.0	0.32	1.11
20	3.1	0.39	1.22
21	4.2	0.63	1.56
22	3.6	0.33	1.12
23	3.4	0.59	1.50
24	5.8	1.11	2.06
25	5.0	0.35	1.16
26	6.3	0.58	1.49
27	2.8	0.29	1.06
Grand Mean	4.2	0.55	1.40

The data presented graphically in Figure 8 shows that as staple CF increases the observed total variance also increases.

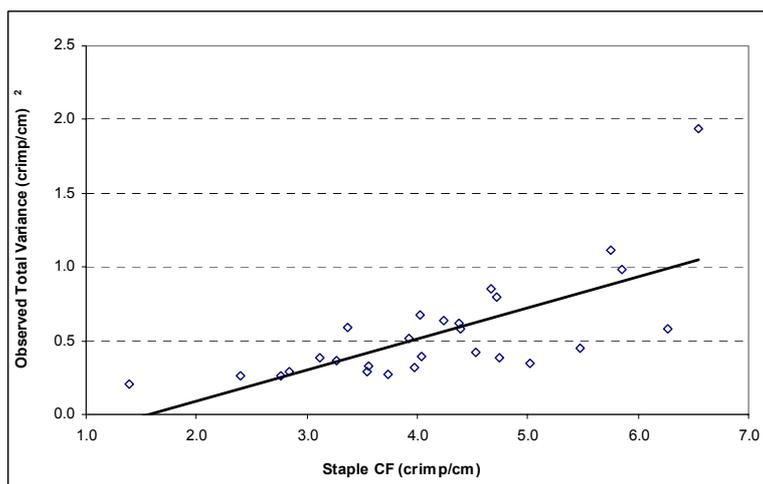


Figure 8. Relationship between staple CF and between-staple-within-lot variance

The data presented in Figure 9 show that the precision of staple CF is dependent on the staple CF. Wool staples with lower staple CF are more distinct and easier to measure, thus the Confidence Interval is smaller for these staples CF's.

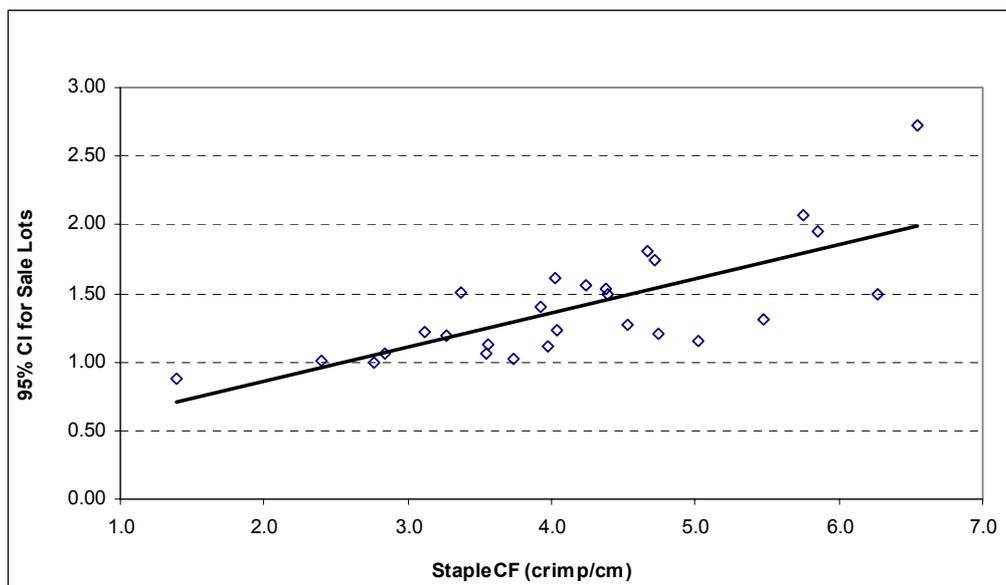


Figure 9. 95% confidence interval of 27 sale lots

Sources of Variation

At this point it is possible to calculate the 95% Confidence Limit for a mean CF determination based on a given measurement strategy (for example, 60 staples, 2 operators and 2 measurements/staple).

Calculations:

$$\sigma^2_{Total} = \frac{\sigma^2_{sampling}}{N_{staples}} + \frac{\sigma^2_{between-ops}}{N_{ops}} + \frac{\sigma^2_{within-staple}}{N_{position}} + \frac{\sigma^2_{within-ops}}{1} \dots\dots[1]$$

The variance estimates can now be substituted into the above equation

$$\sigma^2_{total} = \frac{0.55}{60} + \left(\frac{0.20}{2}\right) + \left(\frac{0.22}{2}\right) + 0.29$$

Therefore

$$\sigma^2_{total} = 0.509$$

The 95% Confidence interval is calculated as

$$95\%CI = 1.96 \times \sqrt{\sigma^2_{total}}$$

$$= \pm 1.4 \text{ crimps/cm}$$

The relative contributions to the total variance for staple CF measurement are listed in Table 5, and Figure 10 shows graphically the breakdown of the contributions to total variation from each source.

Table 5. Summary of Estimated Variance Components and their Contribution to the Confidence Limit of the Mean.

Source of Variation	Variance	Relative	*Variance Contribution to Lot Mean
Between-staple-within-lot	0.55	43.7	0.009 (1.9%)
Within-operator	0.29	23.0	0.290 (62.8%)
Within-staple	0.22	17.5	0.110 (23.8%)
Between-operator	0.20	15.9	0.053 (11.5%)
Total	1.26	100.0	0.462 (100%)

* 60 staples/lot, 2 measurements/staple and 4 operators/lot.

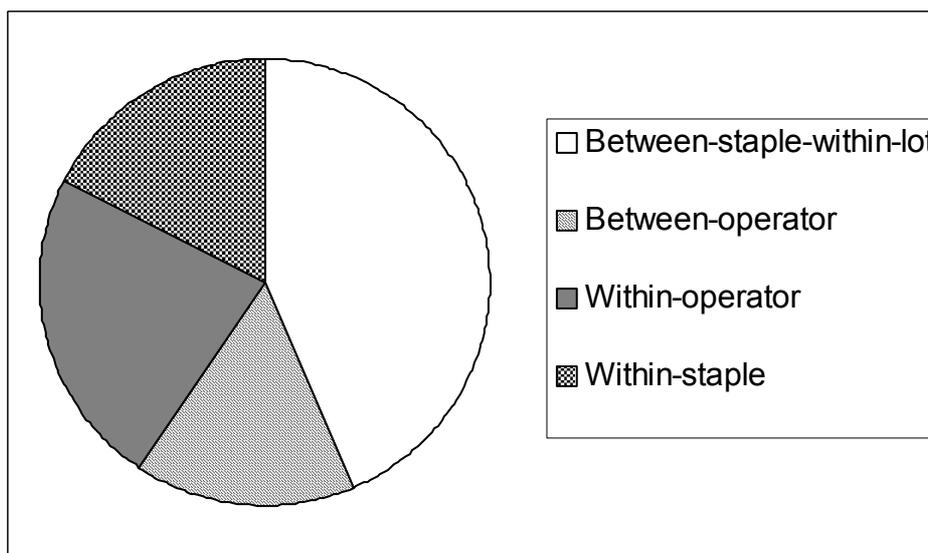


Figure 10. Relative Contribution of the Components of Variation for staple CF

Figure 10 presents the relative contribution of each source of variation from the proposed model. The main source of variation in staple CF measurement lies with the between-staple-within lot variation (43.7%). The within operator and within staple variances are the next 2 largest sources of variation 23.0% and 17.5% respectively. The next most significant contribution to total variance was the between operator variation (15.9%).

For a standard test on a sale lot with 60 staples, 4 operators and 2 measurements per staple the relative contributions to the total observed variance were 1.9%, 62.8%, 23.8% and 11.5% respectively for between-staple-within-lot, within-operator, within-staple and between-operator.

These results suggest that there is scope to improve the precision of staple CF measurement by targeting both the within and between-operator sources of variation. This may be best achieved by the introduction of a crimp meter. For a single crimp meter the variance components due to operators and

the variance between sites within a staple would be zero and the resultant 95% Confidence Interval would simply be calculated as

$$95\%CI = 1.96 \times \sqrt{\frac{0.55}{60}}$$

$$= \pm 0.19$$

CONCLUSION

The trial has produced a set of staples selected according to IWTO-7-00 to evaluate crimp meter. The grand mean staple CF, the observed total variance and the average 95% confidence limit for the grand mean for this set of staples were 4.2 crimps/cm, 0.55 (crimps/cm)² and ± 1.4 crimps/cm respectively.

A model is proposed to estimate the sources of variation in the manual measurement of staple CF. Variance estimates have been calculated for the sources of variation. Other than the between-staple-within lot variance, the within and between operator variances are major contributors to the total observed variance representing approximately 57.7 % and 10.5% of the total observed variance for a standard test (i.e. 60 staples, 4 operators and 2 positions on a staple). The confidence limit for a single sale lot was determined to be ± 1.4 crimps/cm.

The within-staple variance was calculated as 0.22 (crimps/cm)².

The data presented demonstrate that, although time consuming, the manual method reported in this paper provides a relatively precise measure of staple CF on staples prepared for the measurement of length and strength.

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