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The measurement and significance of green sheet properties for the properties of hardened fibre cement

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Abstract

It is common practice for manufacturers of cellulose fibre cement to measure thickness, density and water content of freshly made fibre cement as manufacturing control measures. The thickness of the green fibre cement accurately reflects the thickness in the hardened state and is therefore an instantaneous direct control. However, world standards for fibre cement typically call for fibre cement to be made to a particular strength and although density and water content may be predictive of strength in general, they do not reflect the orientation of the fibres and their contribution to the directional strength of finished product. The purpose of this paper is to introduce two tests of the properties of green fibre cement (green sheet tensile test and green sheet modulus of elasticity) and to show how the properties of the green sheets relate to those of the hardened product. It will be seen that both of these green sheet properties relate directly to the strength of the hardened sheet.

Keywords: Fine reinforced composites; Cellulose; Test methods; Quality assurance; Quality control; Correlation

1. Introduction

The formation of fibre cement by the Hatschek process is quite complex and the appearance of the freshly formed green sheets does not by itself predict the properties of the hardened sheet. Thus it has been common practice to measure the thickness, the density and the moisture content of the green sheet as basic quality measures to control the operation of the Hatschek machine.

Control of the thickness is clearly important to ensure that the sheet meets minimal dimensional standards. Since the thickness of the green sheet is not different from the thickness of the hardened sheet, green sheet thickness is directly predictive of the final hardened sheet thickness. It would be useful to be able to predict the other properties of the hardened sheet and although density and moisture content are partially useful in this regard, they do not predict strength or other mechanical properties except in a very general sense. The purpose of this paper is to introduce two test methods applicable to green sheets and to examine how they may be applied to predict the properties of the hardened sheet.

2. Theory of cellulose reinforced cement composites (CFRC's)

Standards world-wide universally call for fibre cement to be made to specific flexural strengths [1] despite the fact that there are other important mechanical properties that determine the field performance of these

[1] Standards such as, ASTM C1186, Standard specification for flat non-asbestos fibre-cement sheets; ASTM C1225, Standard specification for non-asbestos fibre-cement roofing shingles, shakes and slates; ASTM C1288, Standard specification for discrete non-asbestos fibre-cement sheets interior substrate sheets; AS/NZS 2908.1, Cellulose-cement products—corrugated sheets; AS/NZS 2908.2, Cellulose-cement products—flat Sheets.

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products. Nevertheless the strength of fibre cement is an important control parameter and we will concentrate here on its prediction.

Both flexural and tensile mechanical properties of fibre cement depend on its composition and the orientation of the fibres in the sheet. Fibre orientation depends on the operating conditions within the machine during sheet formation. Thus, the relative strengths in the machine and cross machine directions are determined by multiple factors.

During a flexural or tensile test, the stress carried by the sheet is carried by both the matrix and the fibres until the matrix cracks. The relative amount of stress that is carried by each depends on the relative elastic moduli of the matrix and the fibres, the orientation of the fibres and the proportion of each [1].

Because practical CFRC's contain more than the critical volume [2] fraction of fibre, we may assume that after cracking the matrix does not carry any load and that the entire tensile or flexural load is carried by the fibre. We can also assume that fibres in alternate films are parallel to each other and lying at the same but numerically opposite angles to the machine direction.

Under these assumptions, the ultimate directional flexural or tensile strengths may be predicted by expressions of the following type.

$$\sigma_{\mathrm{CUMD}} = v_{\mathrm{f}} \cdot \sigma_{\mathrm{FU}} \cdot \left(1 - \frac{\ell}{\ell_{\mathrm{c}}}\right) \cdot \cos\theta = v_{\mathrm{f}} \cdot \tau \cdot \frac{\ell_{\mathrm{c}}}{d} \cdot \left(\frac{2 \cdot \ell - \ell_{\mathrm{c}}}{\ell}\right) \cdot \cos\theta \quad (1a)$$

$$\sigma_{\mathrm{CUXD}} = v_{\mathrm{f}} \cdot \sigma_{\mathrm{FU}} \cdot \left(1 - \frac{\ell}{\ell_{\mathrm{c}}}\right) \cdot \sin\theta = v_{\mathrm{f}} \cdot \tau \cdot \frac{\ell_{\mathrm{c}}}{d} \cdot \left(\frac{2 \cdot \ell - \ell_{\mathrm{c}}}{\ell}\right) \cdot \sin\theta \quad (1b)$$

where σ_{CU} = strength of the composite, σ_{FU} = strength of the fibre, v_{f} = volume fraction of fibre, τ = bond strength of fibres to matrix, ℓ = fibre length, d = fibre diameter, ℓ_{c} = critical fibre length, MD = machine direction, XD = cross direction, θ = average angle between fibre and machine direction.

We can use these expressions to estimate the average angle between the fibres and the machine direction from the ratio of the measured strengths in the orthogonal directions. If we define the cross-ratio (XR) as the ratio of the strength in the cross direction to the strength in the machine direction, then the average angle of the fibres (2) is given by

$$\theta = \tan^{-1}(1/XR) \quad (2)$$

The orientation of the fibres does not change once the sheet has been formed on the Hatschek machine and it is reasonable to assume that the length and other properties of the fibres do not change with curing. Therefore, any changes in the measured strengths from sheet to sheet, reflect changes in the bond between the fibres and the matrix, changes in the strength of the matrix or changes in the fibre orientation.

The strain at various parts of the stress/strain curve is also observed to change with time and degree of curing. Strain at failure will be determined by the proportion of fibres that pull out from the matrix during the test and this is determined by the bond of the fibres to the matrix and the length of a specific fibre to the nearest matrix crack. If the load transferred from the matrix to the fibre is insufficient to break it, then the fibre will pull out during fracture of the specimen.

Where a fibre does pull out, the stress at pullout is given by the following general expression and it will be seen that this stress depends on the bond strength.

$$\sigma_{\mathrm{f}} = \xi \cdot \tau \cdot \frac{l}{d} \quad (3)$$

where σ_{f} = stress in the fibre, ξ = efficiency factor related to orientation of the fibre, τ = bond strength of fibre to matrix, l = length of the fibre and, d = diameter of the fibre.

Bond strength increases with increase in the degree of curing of product. Therefore if the properties of the product are followed during the curing period, it will be expected that

- early strengths will be low, fibres will tend to pull out during the test and strains to failure will be high and
- cured strengths will be higher, fewer fibres will tend to pull out during the test and strains to failure will be low.

The fact that newly formed sheets do not disintegrate when handled indicates some bond strength of the fibres to the matrix has already developed. The matrix itself also has some strength due to compaction. Both of these effects are due mainly to surface related forces and only slightly to the permanent bonds and strengths that develop during curing. Therefore given that the fibres do not change their orientation during curing and that curing is a progressive process, the relative directional strengths of the green sheet will predict the relative strengths in the same direction when the sheet is fully cured.

It should be noted that the test does not predict the final strength because we also have to ensure that the curing of the hardened product is not affected adversely by our choice of materials and that the other processes such as curing are properly carried out. It follows that we have to separately ensure the quality of cement, silica and pulp is adequate. Thus irrespective of the final strength, a test of green sheet properties is indicative of the operating conditions in the Hatschek machine and we can use the green sheet test to control these conditions.

We also have to be aware of the amount of water absorbed within the composite at the time of test on the mechanical properties, as this specifically affects both the bond between the fibres and the matrix and the properties of the matrix such as its strength and MoE. However, we can control for the effects of water content by standardising the conditions under which the tests on hardened sheets are carried out.

3. Test methods

3.1. Green sheet tensile strengths

The Hatschek machine off conveyor was stopped and a full width piece of fresh fibre cement sheet approximately 450 mm long was taken from a sheet that had just been removed from the forming roller. The sheet was further sampled by cutting out two pieces approximately 450 mm wide and transported back to the laboratory supported on a flat board. Care was taken to not unduly disrupt the sheet during handling.

Coupons of fresh fibre cement 75 mm by 150 mm were cut parallel and perpendicular to the machine direction using a rectangular wad punch. The specimens were kept from drying out prior to testing by covering with plastic sheet but no other treatment was given. Immediately prior to testing the coupons were uncovered and their width and thickness measured and recorded to the nearest 0.1 mm.

The specimens were loaded into a cam actuated test grip mounted in a plastics tensile testing machine. The specimen was loaded into the grip by moving the ends of the grip apart in the test machine and inserting it into the grip so as not to disrupt its surface or bend it. The bottom eccentric was closed and the two grips were move together by activating the test machine. Once the free end of the specimen was inside the free grip the machine was stopped and the second eccentric was closed. The test machine was activated and the specimen placed in tension and broken. The load at break was recorded and the tensile strength was calculated in the conventional manner and recorded.

Fig. 1 shows the sampling positions and Fig. 2 shows the tensile test arrangement.

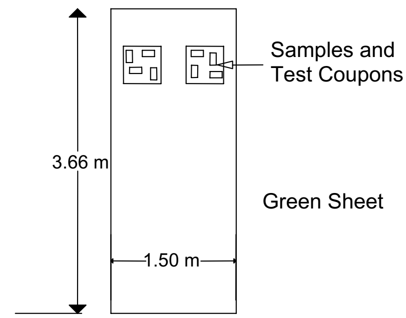

Fig. 1. Sampling position.

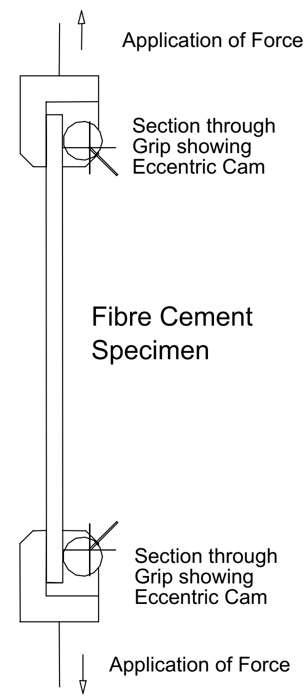

Fig. 2. Green sheet tensile test.

3.2. Green sheet flexural modulus of elasticity

The Hatschek machine off conveyor was stopped and samples taken as described above.

Strips of green sheet were cut approximately 50 mm wide and 300 mm long using a hammer knife. Samples were treated as above prior to testing.

The density of the samples was determined and their width and thickness measured and recorded to the nearest 0.1 mm.

Each strip was placed on a horizontal elevated platform so that approximately 150 mm of the specimen could overhang its edge and that the trailing edge was completely unsupported. The specimen was also placed to be almost touching a sheet of graph paper mounted vertical to the plane of the specimen. The end overhanging the edge of the platform was allowed to droop under its own weight while keeping the other end securely clamped horizontally. The specimen was allowed to come to an equilibrium position and the arc that it made to the horizontal plane was traced carefully onto the graph paper without disturbing its position. Specimens were tested in the machine direction and the cross-machine direction.

Fig. 3 shows the arrangement of the test specimens during the test.

The apparent modulus of elasticity of the specimen was calculated as follows.

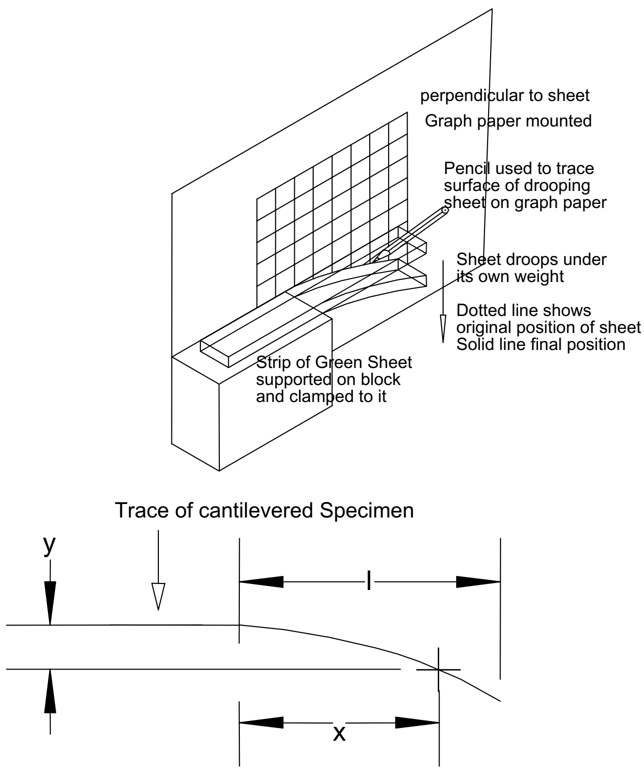

Fig. 3. Deflection of MoE specimen determination of green sheet MoE.

Assuming that the specimen deformed elastically and deflection at any point was due to the sum of the cantilever self-weight of the specimen, the theoretical deflection can be shown to be given by

$$y = \frac{w}{2IE}\left(\frac{1}{2}\ell^2x^2 - \frac{1}{3}\ell x^3 + \frac{1}{12}x^4\right) \tag{4}$$

where w = mass/m^2 of the sheet, I = moment of section of the sheet and, E = the apparent modulus of elasticity of the sheet.

The deflection of the specimen (y) was determined at 10mm intervals from the point of cantilevering (x) of the specimen from the trace from the test above assuming that the deflection of the specimen had minimal effect on the measured overall length of the cantilever (ℓ). The factor in brackets in the equation above was calculated for each "x" and a linear regression forced through zero, was used to fit the measured deflections "y" to determine the slope $\frac{w}{2IE}$. The density and the dimensions of the specimen and the slope of the regression were used to calculate the apparent modulus of elasticity.

4. Comparison with hardened (autoclave cured) fibre cement

Samples were taken of the same batch of hardened fibre cement in an adjoining sheet to that sampled for green sheet properties. Hardened sheets were sampled and cut to size, saturated for 24h in water at 25°C and tested for flexural properties in 3 point bending. A comparison was made of the properties of the hardened fibre cement and the green sheet to see if the hardened sheet properties could be predicted from those of the green sheets.

5. Test results and analysis

5.1. Green sheet tensile vs hardened modulus of rupture (MoR)

Table 1 below shows a comparison of the green sheet properties with the MoR of the same sheet that has been cured and hardened. Mechanical strengths are shown in the green and hardened states in both the cross and machine directions.

5.2. Analysis of the results

5.2.1. Correlations between the variables

Table 2 shows the partial correlation coefficients between the variables. For the purposes of this analysis, the tensile and flexural strengths were aggregated into one table of values.

It will be seen from the table that the only variables that are significantly correlated are

- Moisture content and the density of the sheet and
- MoR (hardened flexural strength) and the green sheet tensile strength.

It would be expected that the moisture content would tend to decrease as the density increases given that the nominal formula of the mix was the same in all cases even though the cellulose content varied. This is expected because the sheet is compressed during formation and the removal of more moisture will compact the sheet and increase its density. The relationship is shown in Fig. 4 below where it will be seen that there is considerable scatter. (Note that only 8 points are shown despite there being 18 points in the tensile data. This has occurred because the 18 points of tensile data represent 9 samples of data in each of the machine directions and one outlier has been eliminated.)

It is significant that the second most important determinant of density is cellulose content and that the correlation coefficient also shows that decreasing cellulose content increases the density. It may be expected that there will be a better correlation between the density and a combination of cellulose and moisture content but this is not explored here.

Table 1
Green sheet and hardened sheet compared

Specimen number	Green sheet properties					Hardened properties	
	Moisture (%)	Density (kg/m^3)	Cellulose (%)	Tensile strength (kPa)		MoR (MPa)	
				XD	MD	XD	MD
1	37.9	1558	7.5	3.1	8.0	6.5	11.3
2	36.4	1624	7.7	2.9	7.5	9.2	15.7
3	38.3	1615	7.8	3.5	8.7	7.0	11.3
4	42.7	1633	7.9	3.1	6.7	7.3	11.6
5	40.6	1591	8.0	3.3	6.7	7.9	12.4
6	36.2	1585	8.0	3.2	7.7	7.1	12.5
7	39.2	1557	8.1	3.5	7.4	6.6	11.0
8	37.9	1618	8.1	3.2	6.6	7.6	12.8
9	37.1	1589	8.1	2.9	7.2	8.7	13.4
10	35.6	1637	8.1	3.3	8.1	7.4	11.8
11	37.9	1613	8.1	3.2	7.8	6.9	11.9
12	47.6	1505	8.2	2.9	6.3	7.7	13.0
13	36.8	1622	8.2	2.8	5.9	7.7	12.9
14	45.1	1526	8.4	2.9	7.5	7.4	13.1
15	38.8	1585	8.5	3.2	7.0	6.7	12.6
16	41.6	1628	8.5	3.5	7.4	7.8	11.9
17	40.7	1615	8.6	3.3	7.8	7.1	12.1
18	45.3	1517	8.7	2.6	8.2	9.2	15.6
Statistics							
Maximum	47.6	1637	8.7	3.5	8.7	9.2	15.7
Minimum	35.6	1505	7.5	2.6	5.9	6.5	11.0
Average	39.8	1590	8.1	3.1	7.4	7.5	12.6
Std Dev'n	3.5	41	0.3	0.3	0.7	0.8	1.3

Table 2
Correlation matrix

	MoR	GS tensile	Moisture	Density	% Cellulose
MoR	1				
GS tensile	0.8821	1			
Moisture	0.0648	−0.0399	1		
Density	−0.0700	0.0214	−0.6653	1	
% Cellulose	0.0866	−0.0233	0.4492	−0.2057	1

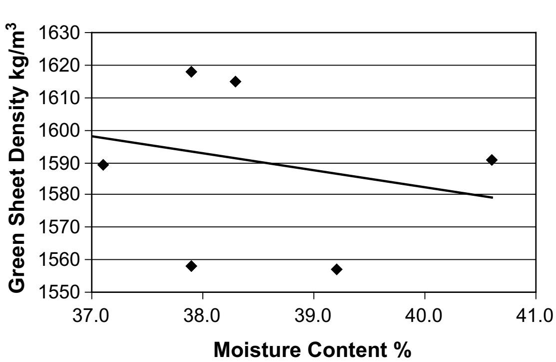

Fig. 4. Green sheet density vs water content.

5.2.2. Significant relationships

The relationship between the green sheet tensile strength and the MoR is most significant and it clearly shows that there is a direct relationship between these measures. Cellulose content has a small effect on the MoR but the density is not particularly significant. To some extent this is due to the aggregation of the numbers in the analysis as this splits the results into two groups associated respectively with the cross and the machine direction strengths. (Fig. 5). However, the results clearly show that there is a strong correlation between the measured green sheet tensile directional strengths and the corresponding directional strengths of the hardened sheet.

The results can be explained in the fact that the cellulose fibres are the principal contributors to the strength of the final composite and that the development of strength is due to the progressive development of bond

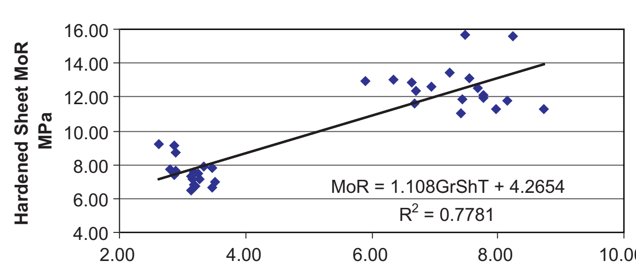

Fig. 5. Hardened sheet MoR (Mpa) vs green sheet tensile (kpa).

between the matrix and the fibres during curing. The difference between the machine and the cross directions is most apparent and this is due entirely to the orientation of the fibres relative to the machine or the cross directions. The green sheet tensile strength can therefore be used to determine the proper operation of the fibre directional devices within the operating machines. It can also be used to give an indication of the final strengths of the hardened products.

Fig. 5 shows the relationship between green sheet tensile strength (kPa) and the final hardened flexural strength. The regression equation relating these parameters explains a little less than 80% of the total variation of MoR. There is however a considerable scatter of results about the trend line and clearly there are other factors that are affecting our prediction. It has been inferred above that it is necessary to control other parameters in the preparation of the raw materials and the formation on the machine, so this is not particularly surprising since the results presented here were gathered over an operating period of approximately one week.

It is also important to note that we are comparing the flexural strength of the hardened product with tensile strength in the green product and that a better correlation could be expected between a hardened tensile strength. Unfortunately tensile data from hardened sheets was not available and this comparison could not be made.

5.3. Green sheet modulus of elasticity

Table 3 presents the results of the measured deflections of one set of specimens of 8 mm thick green sheet together with the calculated values of the bracketed factor in Eq. (4) above. A set of data is given for the cross and the machine directions. The graphs in Figs. 6 and 7 show the deflection.

Table 4 shows the results of the calculation of MoE and comparison of the green sheet MoE with typical hardened sheet properties. It is clear that the regression calculation to determine the slope of the deflection/factor curve is very significant and the actual and expected deflections are close to identical. We can therefore conclude that the deflection of the specimen can be represented as though it is elastic.

It may be noted that the author found that it is necessary to limit the amount of overhang to avoid breaking of the specimens and that the allowable overhang seems to be related to thickness of the specimens. It is probable that the overhang of specimens may have to be adjusted in accordance with thickness to maintain specimens in the elastic range.

The comparison of the green and hardened specimens is quite interesting. The MoE of the hardened and the fresh specimens are not closely correlated, however the apparent green sheet MoE is correlated with the final hardened strength. Since hardened MoE is a truer measure of MoE in this case, this implies that the mechanism of deflection of the green sheet depends more on the fibres than the matrix. Hardened MoE is determined from the slope of the first approximately elastic portion of the stress/strain curve and is dependent on the matrix as well as the fibres. Thus there is little difference between the machine and cross direction MoE's.

In the green state however, the tensile strength of the matrix can be considered to be almost zero and the entire stress in the specimen is taken by the fibres. The compressive strength of the reinforced matrix can however be considered high due to point to point contact of the non-fibrous material held in place by the fibres. Thus

Table 3
Results of green sheet MoE measurements

Cantilever, mm	Bracketed factor	Deflection, mm						
		Cross direction				Machine direction		
		#1	#2	#3	Average	#1	#2	Average
0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1075833	−0.5	−1.0	−1.0	−0.8	−0.5	−0.1	−0.3
20	4113333	−1.8	−2.5	−1.8	−2.0	−1.2	−0.8	−1.0
30	8842500	−3.5	−4.2	−3.5	−3.7	−1.8	−1.5	−1.7
40	15013333	−5.0	−6.3	−5.8	−5.7	−2.3	−2.1	−2.2
50	22395833	−7.5	−8.7	−8.0	−8.1	−3.0	−2.7	−2.9
60	30780000	−10.1	−11.5	−10.5	−10.7	−4.0	−3.5	−3.8
70	39975833	−12.0	−14.5	−13.5	−13.3	−5.0	−4.2	−4.6
80	49813333	−14.5	−17.0	−16.0	−15.8	−5.8	−5.0	−5.4
90	60142500	−18.5	−20.0	−19.0	−19.2	−6.8	−5.7	−6.3
100	70833333	−19.5	−23.5	−21.0	−21.3	−7.7	−6.7	−7.2
110	81775833	−21.5	−26.2	−23.0	−23.6	−8.0	−7.8	−7.9
120	92880000	−23.5	−29.0	−25.0	−25.8	−9.0	−8.4	−8.7
130	104075833	−25.5	−31.7	−27.5	−28.2	−10.5	−9.2	−9.9
140	115313333	−28.0	−34.0	−30.0	−30.7	−11.8	−10.6	−11.2
150	126562500		−38.0			−13.3	−13.0	−13.2

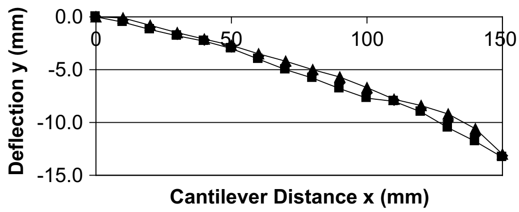

Fig. 6. Machine direction deflection vs cantilever.

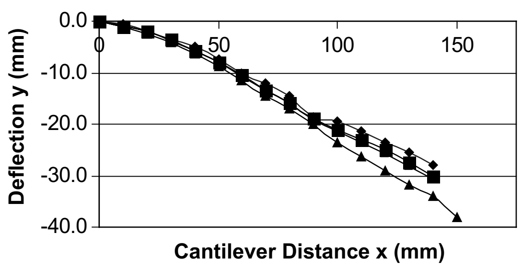

Fig. 7. Cross direction deflection vs cantilever.

Table 4
Calculation of MoE and comparison

	MD	XD
Slope of deflection/factor curve	−9928663	−2998188
Apparent MoE N/mm2 (MPa)	15.5	8
Regression statistics		
Multiple R	0.992822	1
R Square	0.985696	1
Typical hardened sheet properties		
MoR (MPa)	11.4	7.4
MoE (GPa)	4.1	3.9

the green specimens deflect as though they were elastic aggregates of the fibres. Thus the MoE reflects the fibre content and orientation and ultimately is better correlated with hardened strength.

6. Conclusions and final remarks

6.1. Conclusions

It can be seen from the above that the mechanical properties of the green sheets reflect the same properties in the hardened sheets. Thus the measured properties of the green sheet can be used to ensure that sheets are being properly formed on the production machinery before they are put to the expense of curing.

That the properties of the green sheet reflect those of the hardened sheet should not be surprising, since the properties of the hardened sheet are determined in the main by the development of bond strength between the fibres and the matrix. Providing nothing happens to alter the course of normal development of bond and matrix strength, it should be possible to observe a progressive change in the properties of the sheet with curing up to a limit determined by the ability of a maximally bound fibre to carry load.

The two test methods proposed give predictive results of the strength of the hardened properties. Direct tensile strength is easier to calculate but requires additional equipment for its performance. The measurement of apparent MoE is extremely simple but requires more sophistication in the calculation although it should be easy to automate this with modern computers.

6.2. Final remarks

Only limited data is presented here and there is a need to extend the scope of the investigation. It would be useful to extend the investigation to include the comparison of direct tensile strengths and strains of green sheet and hardened sheets as this may prove more fruitful than the present techniques to the understanding of the mechanisms at work during failure of specimens.

It would also be useful to carry out more extensive work on the relationship between the cross and machine direction measurements to assess the accuracy of the predictions. Extension of the present work is recommended.

Having said that however, it would appear that the MoE test is predictive, is easily within the scope of most laboratories and requires little equipment for its implementation.

A word of warning may be added in conclusion because it is common in the industry to find that sheets may fail by delamination. This may occur even with otherwise perfectly formed sheets and is often due to the use of "stale" mix after a shutdown. It is not known whether the results presented here would reflect poor interlaminar bond formation although since they were carried on good sheet, but it is expected that the MoE test would give some early indication. It would be useful for the manufacturer to have a predictive green sheet ILB test that could point to problems in the hardened sheet. A peel test similar to that used to test adhesives could be useful, however some work would need to be done to develop and standardise it.

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