An Experimental Analysis of the Zero and Short Span tensile tests

MSc. Thesis

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ABSTRACT

The pulp and paper industry seeks for a fast yet reliable method to access mechanical properties of pulp fibres in order to develop fibres for different papers and end use applications. The zero and short span tensile tests are suggested as one method to obtain mechanical properties of the fibres in a paper.

The aim of this study is to analyse these test methods experimentally using three samples and create an experimental base for further numerical and analytical studies.

The samples consist of a laboratory made paper having a random fibre network structure, a machine made orthotropic grease proof paper and a homogeneous isotropic aluminium foil.

The effect of different span lengths, thickness and clamping pressure on the stress-displacement response in a short span tensile test is investigated. Also the effect of slippage of the specimen under the jaws is analyzed by varying the clamping pressure.

Results obtained from the experiments show that the zero and short span tensile strength of paper is sensitive to the stress fields, which depend on the plasticity of the material, thickness, span length and slippage.

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1 INTRODUCTION

For many years single fibre tests are used to measure the mechanical properties but they have three main drawbacks. One is that it is tedious; two is that more than 300 fibres are required to test in order to get a distribution curve and representative mean values for fibre strength and strain at break. The third reason is that the single fibre is dried restraint and different from a fibre in a typical paper sheet, which may lead to that the fibre tested in a single fibre tester may not be representative for a typical fibre in the sheet. One way to over come these obstacles is to use a short span test on a piece of paper so that most fibres bridge the gap between the jaws. The drawback of this method is a tri-axial stress state in the specimen because of the boundary conditions, which make it difficult to interpret the data.

1.1 Paper properties

Paper is made from wood fibres that consist of cellulose, hemicellulose and lignin. The fibres are held together by fibre to fibre joints where hydrogen bonds likely play a role. Lignin rich pulps have a high yield. The drawback with lignin is that it turns brown during cooking and it becomes yellow when exposed to light in mechanical bleached pulps. Depending on the paper type, several processes are carried out on the pulp before making it into paper. They can include:

Bleaching: - which makes the pulp white usually by a chemical process that removes lignin

Refining - this is done to make the fibre flexible, roughen the fibre surface and to create fines in order to increase density of the sheet and increase fibre bonding.

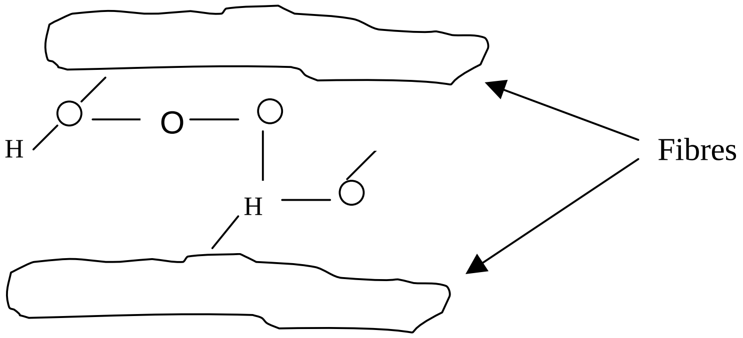


Figure 1: Hydrogen bonds that may form between fibres

Paper is not a uniform material. Non-uniformity is built into the paper already during the formation of paper in the paper machine. Also the fibres are non-uniform with a distribution curve for fibre length and thickness.

Anisotropy of paper

Anisotropy means that a material has a different mechanical response in different directions. In paper this is due to fibre orientation, which is the direction in which the fibres in the sheet are aligned. Paper made in a paper machine has more fibres aligned in the *Machine Direction* (MD), which is the direction of flow in the paper machine and less fibres aligned in the *Cross Direction* (CD) which is perpendicular to machine direction. As for laboratory made hand sheets, the fibre orientation is random. Machine made paper is stronger in MD than in CD because of fibre alignment. The strength of a randomly oriented sheet is the same in all directions and should be 1/3 of that of a completely oriented sheet in the fibre direction [1].

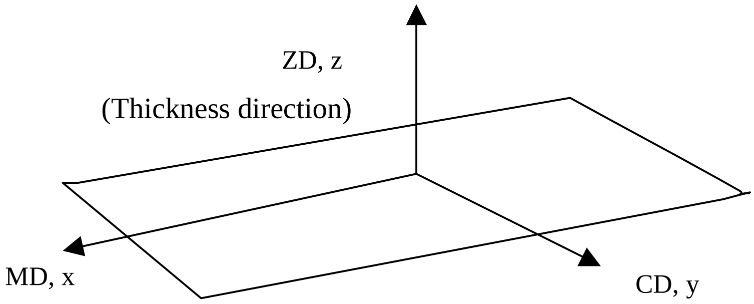


Figure 2: The directions in paper

Paper Strength

Defects like kinks and curls in fibres reduce paper strength because they give rise to weak points in the fibre that will reduce fibre strength. The increase in tensile strength of paper with beating or refining comes from straightening of fibres, making the fibres more flexible, removal of kinks and curls and increased fibre joint strength through fibre surface roughening [2].

Hydrogen bonds require close contact between the fibres in order to be established. Therefore an increased number of hydrogen bonds may play a role for increased fibre joint strength when the fibres are beaten. Beating of pulp increases the possibility for fibre surfaces to come in close contact with each other.

The strength of paper is controlled by mechanical properties of the fibres, fibre joint strength, fibre dimensions and structure. Van den Akker [3] showed that in tensile failure of paper, a considerable percentage of fibres in the zone of rupture fail rather than pull out even in sheets where the degree of bonding is only moderate. Both fibre length and inter-fibre bonding affect fibre pullout. Shorter fibres have less bonding points to adjacent fibres than longer fibres and poorly bonded networks will exhibit more fibre pullout than well-bonded networks. Fibre to fibre bonds can have appreciable shear strength, which means the bonds may remain intact until the fibre failure stress is reached [4]. Also if fibre bonds are sufficiently strong to withstand any level of stress transfer from one fibre to the next, it is then obvious that the fibre tensile strength is related to sheet tensile strength [5].

1.2 Zero Span Tensile Test

The Zero span tensile test was introduced as early as 1925 by Hoffman-Jacobsen to distinguish the difference between the strength of the fibre network and strength of the fibres themselves. Later on in 1958, the Van den Akker's group [3] studied the parameters affecting the test and proposed a model for it. In a ZST the clamping jaws of the tensile tester are brought into contact and clamped to the specimen in such a manner that the resultant tensile force is applied across a plane through the thickness [1]. It is also assumed that all the fibres in a zero span tensile test contribute to the failure at load since they are all clamped at both ends.

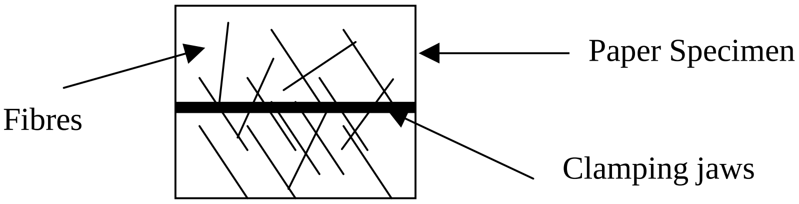


Figure 3: Diagram showing the clamping jaws in contact at the start of a zero span tensile test

Fibres in a sheet of paper are not equally strong; some fibres reach their ultimate strength before others during straining. As the strain increases, the load carried by the sheet continues to rise as long as the incremental load increase in unbroken fibres compensates for the loss due to broken fibres. When the stress developed in fibres reaches the ultimate stress of the majority of fibres, the increase in load cannot compensate for the broken fibres and the paper fractures. This maximum stress is the zero span tensile strength [6].

According to Mohlin et al [2], zero span tensile strength is influenced by fibre kinks and curls. In general, the zero span tensile strength increases after mild refining of the fibres which reduces kinks and straightens the fibres [7] hence increasing the number of fibres that can be loaded during the test.

A specimen in a ZST test sees a larger span than the distance between the clamps because of slippage under the jaws [7]. The difference between the clamping span and the true span that the specimen sees, is the *residual span.* This explains the high measured displacement at break in a ZST test. The boundary conditions and the plane strain condition in the ZST-test gives 30% higher tensile strength than the long span tensile test according to a simplified model [9]. In zero and short span tests, the paper is constrained by the jaws thus lateral contraction is prevented, which only gives a uniaxial strain condition. However the long span tensile test gives at maximum a tensile strength value less than 70% of ZST strength due to bond failure and an increased possibility of finding a weak link.

1.3 Short Span Tensile Test

In short span tensile tests, the tensile strength is measured when the clamping jaws have been set apart to a certain span.

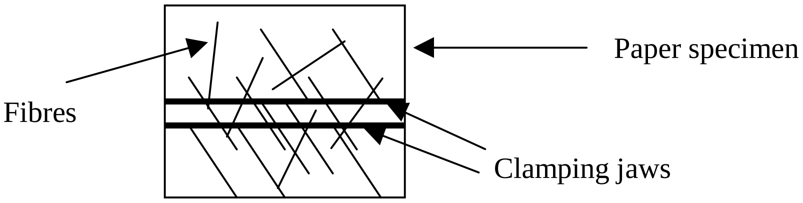


Figure 4: Diagram showing the clamping jaws apart at the start of a short span tensile test

In a bonded network, short span tensile strengths converge to the tensile strength of the paper when the span increases while for an unbonded network it declines to zero if the span exceeds the length of the longest fibre [5].

Cowan [5] suggested that the degree of bonding in a fibre network can be obtained from the ratio between dry to wet short span tensile strength. Gurnagul and Page [10] argued against this and showed that the difference between the wet and dry tensile strength is not due to loss of bonding but depends more on the extent of mechanical and chemical damage to the fibres during pulping, bleaching and refining.

In summary, the short span tensile response of paper depends on the strength of the inter-fibre bonds, the fibre length, fibre orientation, fibre curl and fibre strength.

1.4 Long Span Tensile Test

In a long span tensile test, the span length between the two clamping jaws is typically 100mm long and 15mm wide. A uniaxial stress field prevails because of the narrow and relatively long specimen. Influences from clamping boundaries are negligible and the specimen contracts in width when stretched.

1.5 Clamping pressure, thickness and span length

When the clamping pressure is applied on the jaws in a ZST-test, a slight movement of the jaws occurs because the paper specimen is squeezed out from the clamps when the clamping pressure is applied. There is also a slippage that pulls the paper out from the clamps when sufficient tensile load is applied under the test. An increased clamping pressure reduces the slippage and thereby the measured displacement and residual span [7].
Also increased clamping pressure increases tensile failure load since more fibres are securely clamped and do not slip [5]. A very high clamping pressure causes damage to the fibres, this damage is called *compressive damage* and it reduces tensile strength. The ability of the fibres to resist compressive damage sets an upper limit on the amount of clamping pressure that can be applied. Furthermore an upper limit will ensure that a significant residual span will exist at tensile failure [7]. Wink and Van Eperen [11] found that inflection along the grips caused stress concentrations and reduced the strength considerably. Therefore clamping jaws should be free of any friction reducing agents and the clamping pressure should be adjusted to a level where the tensile strength of the specimen is on a plateau.
The diagram below by Cowan [5] illustrates what happens when clamping pressure is applied during a zero and short span tensile test.

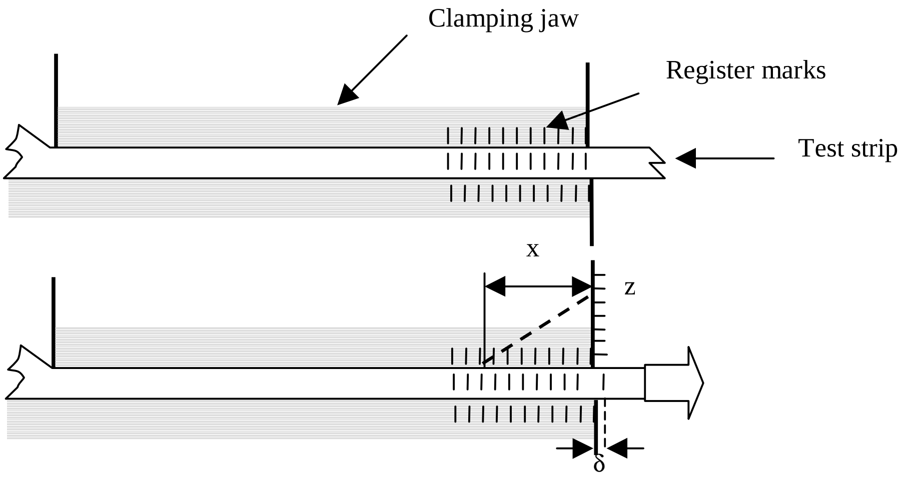


Figure 5: Friction model by Cowan

In the diagram, the register marks are used to show the relative position of the test strip and the clamping jaws during straining. The paper is held in position under the clamps by friction. A force balance and law of friction give that the length, *x,* required to hold the specimen is the zero span load, F_Z , divided by clamping pressure, P_C , and *2.* The factor two comes from symmetry because slippage occurs on each side where the specimen is in contact with the clamp. Register marks beyond this distance remain lined up since no relative motion occurs. Prior to this point, the marks in the paper are displaced forward with the result that a finite elongation of δ shows up as *slippage* from under the jaws.

Batchelor and Westerlind [12] suggested a method to obtain the force-displacement curve of the free span (specimen between the jaws). The procedure is to subtract the zero span displacement from the short span displacement at the same load and repeating this procedure over the whole force range. This method assumes that the stress distribution through the thickness of the sample is the same and independent of span length, which may not necessarily be true. Another assumption is that the slippage under the jaws is the same for all span lengths and the subtracted curve should relate to fibre strength alone and should neither depend on fibre length nor on the degree of bonding between the fibres. Also, the subtracted stress-strain curve should be independent of span length if the assumptions are correct.
Hägglund, Gardin and Trakameh [13] argued that the contribution from slippage to the total span elongation depends strongly on the span length. They further suggested that the stress field through the thickness direction in the sample is not uniform and that two samples having identical properties but with different thickness show different mechanical response at a given span length. The thinner sample will exhibit higher strength and stiffness because of a flatter stress profile.

2 MEASURMENTS AND UNITS

2.1 List of measured parameters and their units

- P_c, clamping pressure in *megapascal (MPa)* is the amount of pressure that is applied on the clamps and is used to hold the test piece in place while running the test.
- ***G*** **,** span length in *micrometer (μm)* is the distance between the two clamping jaws before running the tensile test
- ***b*****,** specimen width in *millimetre (mm)* is the width of the specimen that you place under the clamps. It is usually the same as the width of the clamps.
- ***w*****,** grammage is calculated as mass per surface area. The unit is *grams per square metres (g/m²)*
- **t,** thickness in *micrometer (μm)* is measured in the z direction of the specimen.
- **μ,** Friction coefficient. There are of two types, static, μ_s, and kinetic, μ_k. The static friction is the friction between two surfaces in contact at the start of motion, while the kinetic friction is the friction between two surfaces while in motion.
- σ^b , tensile strength is the maximum force per unit width that a specimen can resist before breaking when applying the load parallel to the length of specimen. The unit is *Newton per centimetre (N/cm)***.**

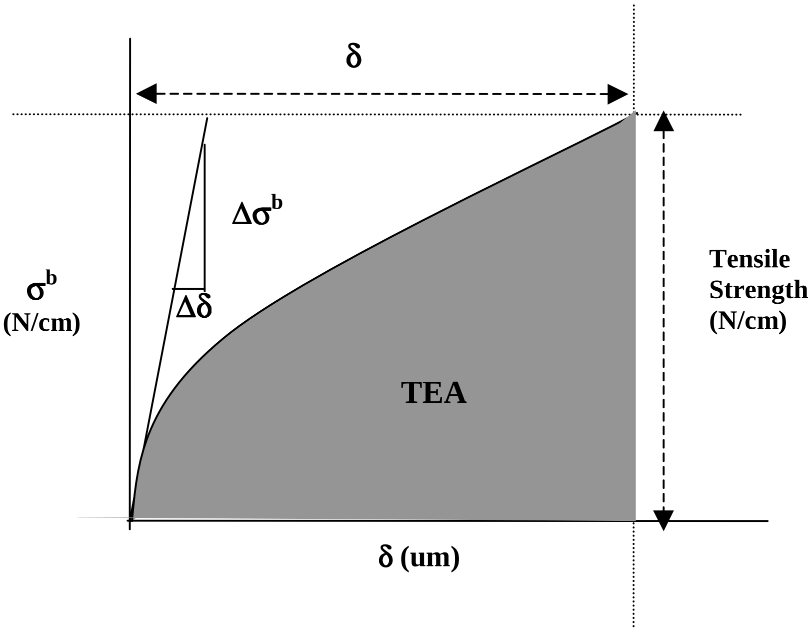


Figure 6: Stress-displacement curve for paper

- σ^w , tensile index relates the strength to the weight of the material being loaded. It is also referred to as specific stress**.** The units are *kilonewton-metre per kilogram (kNm/Kg).*

$$Tensile\ index(kNm/kg) = \frac{tensile\ strength\ (N/cm)}{grammage\ (g/m^2)} \times 100 \qquad \textbf{\textit{(1)}}$$

- **δ,** displacement in *micrometer (μm)* is the extension of the sample from its original length.

Displacement: $\delta = \mathrm{L} - \mathrm{L}_0$

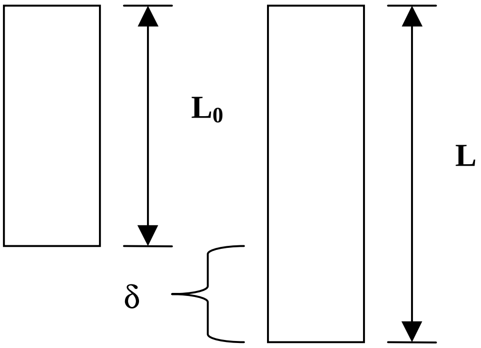


Figure 7: Displacement δ for a specimen under stress

- **TEA,** tensile energy absorption here refers to the area under the force-displacement curve. The tensile energy absorption is related to the toughness of the material because it measures how much energy a sample can absorb before it breaks. The integral is the work (energy) required in breaking the sample and the units are *Newton (N).* [Figure 6]

$$\textit{Tensile Energy Absorption}\,(N) = \int_{0}^{\delta_{\max}} \sigma^{b}(\delta)\ (\mathrm{N/cm}) \times d\partial\ \ (\mu\mathrm{m}) \times 0.0001 \qquad \textbf{\textit{(2)}}$$

- **s,** tensile stiffness is the slope (gradient) of the elastic (linear) part of the curve. It is used to characterise the elastic part of the mechanical response for materials. The unit here is N/cmµm because of the problem to access the original length of the specimen, which includes the free and residual span.

$$\textit{Tensile Stiffness}(N/cm\mu m) = \frac{\Delta F\ (N/cm)}{\Delta\delta\ (\mu m)} \qquad \textbf{\textit{(3)}}$$

- **E,** elastic or Young's modulus is the initial slope of a stress strain curve. It is also referred to as the elasticity or the tensile modulus. Stress-displacement curves are usually non-linear with a tangent that changes with the amount of displacement. The maximum at low strains is the modulus. Young's modulus has the units of megapascal (MPa) and is calculated from tensile stiffness by dividing it with the thickness of the specimen and original length. [Figure 6]

$$\textit{Young's Modulus}(MPa) = \frac{\textit{Tensile stiffness}\ (N/cmum) \times 100}{\textit{Original length}\ (\mu m) \times \textit{Thickness}(\mu m)} \qquad \textbf{\textit{(4)}}$$

3 EQUIPMENT

The two tensile testers used in the experiment were the Z-Span 2000 tensile tester from Pulmac Instruments Corporation and a loading frame from MTS System Corporation. The latter was equipped with specially designed grips for zero and short span tensile tests. The Pulmac tensile tester operates under force control while the MTS operates under displacement control. The size and shape of the clamping jaws and clamping pressures for the two devices differ. Also they use different computer software to collect the data.

3.1 Pulmac Tensile Tester

In the early 1970’s, Pulmac developed a new zero span tester and initiated an in depth study of the ZST. Over the years Pulmac continued the practical development of the tensile strength measuring equipment. The Pulmac tensile tester makes 24 tests on three circular specimens, 8 on each specimen in an automatic sequence. Alternatively, one large rectangular specimen instead of 3 smaller circular specimens can be used which is preferable when machine made papers or orthotropic materials are to be tested. This is made possible since the tensile tester comes with an in-built XY-table, [Figure 9], where you can place the sample between two plastic sheets having 24 windows. The tester positions each window by the XY-table under the 22mm wide clamps and then applies a clamping pressure and a tensile force while measuring load and grip displacement. The computer then draws a graph of the tensile force-displacement curve.

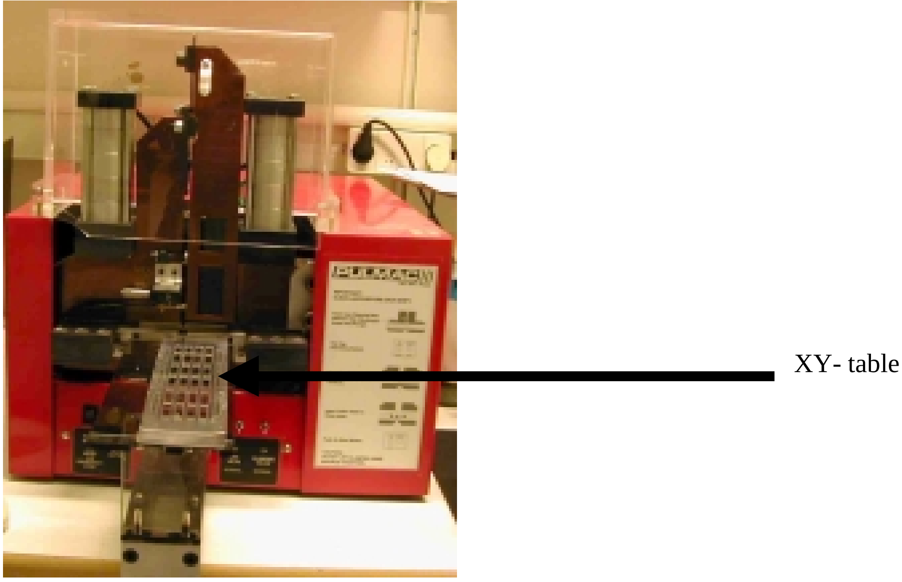


Figure 8: The tensile tester from Pulmac

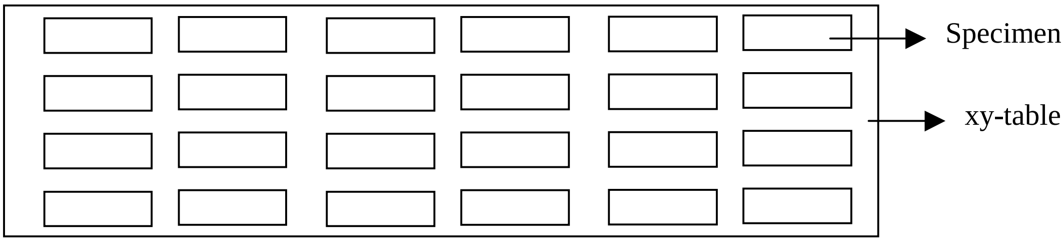


Figure 9: The XY-table on the Pulmac where you place the sample that consist of either three circular specimens or one rectangular specimen

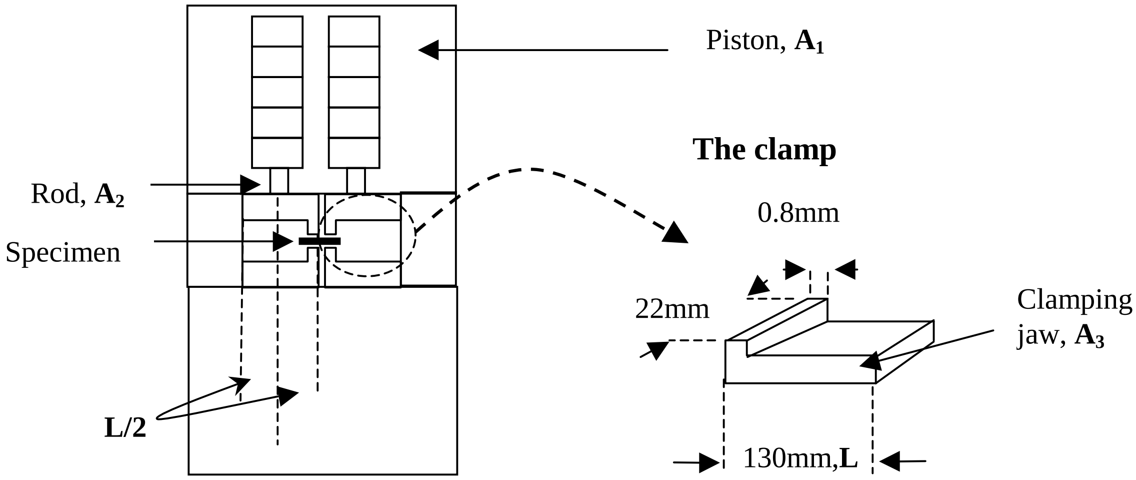
3.1.1 Control Mechanism

This Pulmac zero and short span tensile tester carries out the tensile strength test under force control. A pneumatic cylinder applies a force to the moveable clamp that will pull it away from the stationary clamp. The air pressure is measured and converted to force, which is applied at a rate of 22-24 N/ms (Newton per millisecond) until the sample breaks. The effect of force control on the force-displacement curve is that the displacement increases at a faster rate in the beginning of the test and then slower towards the end while the force increases at a constant rate.

3.1.2 Clamping jaws and Clamping Pressure

The clamping jaws have a width of 22mm and length 0.8mm. This is the size of the part of the jaws that clamps the specimen.

Figure 10: The Front view of the Pulmac tensile tester



$$P_c\ (N/m^2) = {}^{F_1}\!/_{2} \times A_3 \qquad \textit{(5)}$$

where

- A_3 = area of the clamping jaw ($0.8\text{mm} \times 22\text{mm}$)
- ${}^{F_1}\!/_{2}$ = force applied on the clamping jaw.

The force is applied at the centre of the clamp.

- F_1 = total force applied on the clamp

  $p \times 5\ (\textit{no of pistons}) \times (A_1 - A_2)$
- A_1 = area of the piston (diameter = 4.0625mm)
- A_2 = area of the rod in the piston (diameter = 0.9375mm)
- p = Applied air pressure in Pa (1psi = 6894.76 N/m^2 or Pa)

The applied air pressures were 90, 80, 60 and 40 psi that correspond to clamping pressures of 109.7, 97.5, 73.1 and 48.7 MPa. Normal setting for air pressure on the Pulmac is 80 psi, which is a clamping pressure of 97.5 MPa.

3.1.3 Force and Displacement Calibration

The force was calculated from the pressure in the pistons driving the jaws apart. The separation of the jaws was continuously measured by a Kaman Multi-VIT (Multi-purpose Variable Impedance Transducer) model KD2300. This is a contactless displacement transducer, which was attached to the moving jaw and provided a measurement of position relative to the stationary jaw [12]. Both force and displacement are measured as voltages.

The conversion from voltage to micrometers is done using a calibration curve that was obtained by fitting a cubic smoothing spline curve to a set of calibrated distances between the clamps. The routine (csaps) in the Matlab software is used with the smoothening parameter set to 0.999. The value for the smoothening parameter is not critical and is chosen in order to give a smooth curve that best fits the data as closely as possible.

The measuring range for the displacement sensor is roughly 1100µm with this calibration procedure while the linear range for the sensor is 1000µm. This means that very soft material for which the sum of span length and displacements due to straining exceeds 1100µm cannot be tested. This also limits the maximum span length that can be set in the Pulmac tensile tester.

3.2 MTS Tensile Tester

A test frame equipped with clamps for zero and short span tensile test is fixed vertically on an MTS 4/ML testing device. This tensile tester tests one specimen at a time during one test run unlike the Pulmac tensile tester which tests 24 specimens during one test run. This is a disadvantage since it is more time consuming. Also, variations may occur in the placement of the specimen between the grips although special care is taken. These variations may cause additional spread in the data. Taking into consideration these factors, ten specimens were tested and out of these only the specimens with a covariance of less than 5% were selected. Specimens of size 15 mm in width by 45mm in length were used.

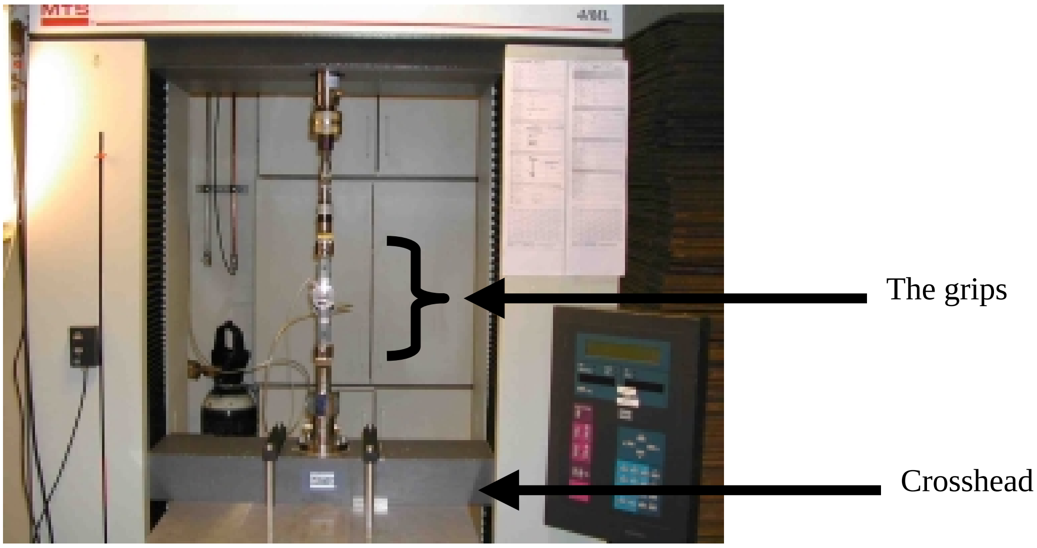


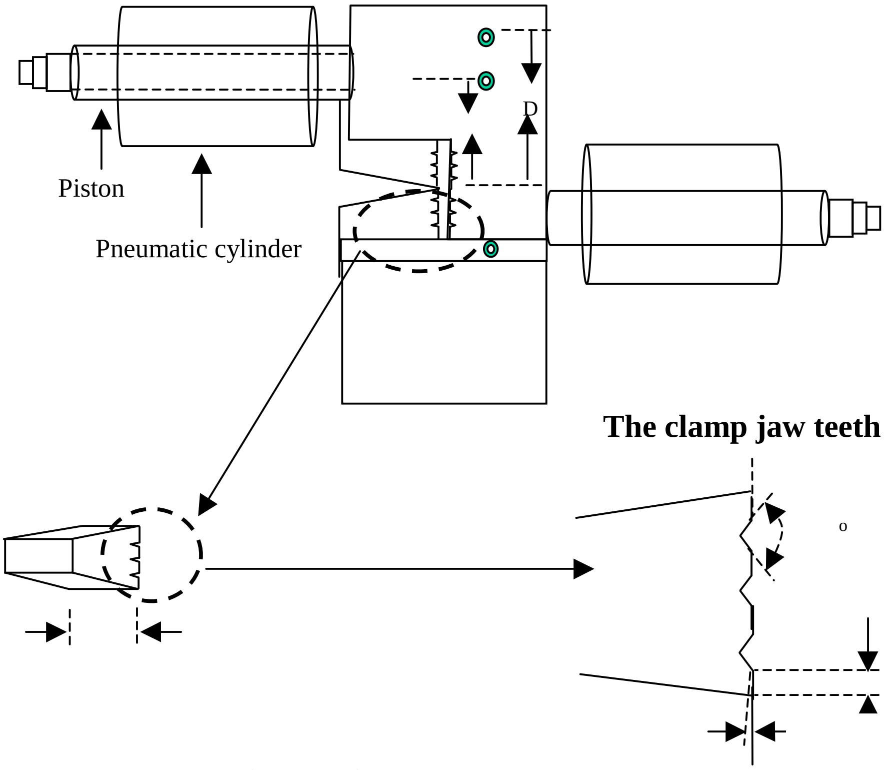
Figure 11: The loading frame from MTS equipped with zero and short span grips

3.2.1 Control Mechanism

This instrument carries out the tensile strength test under displacement control. This means that the movement of the crosshead controls the movement of the clamping jaws apart. The crosshead moves apart at a constant rate until the sample breaks. Displacement control has the opposite effect compared to the force control. Force increases at a higher rate in the beginning and then slower towards the end while the displacement increases at a constant rate.

3.2.2 Clamping jaws and clamping pressure

Figure 12: A side view of the MTS grips



$$P_c\ (N/m^2) = {}^{d}\!/_{D} \times \frac{p(A_1 - A_2)}{A_3} \qquad \textit{(6)}$$

where

- A_3 = width of the first jaw tooth × length of the grips (1mm × 15mm)
- A_1 = area of the pneumatic cylinder (diameter = 45mm).
- A_2 = area of the piston in the pneuamatic cylinder (diameter = 12mm)
- p = applied air pressure
- d = length of the clamp
- D = distance from piston to clamp

The applied air pressures were 3, 5 and 6.5 bar, which correspond to 28.7, 45.5 and 53.8 MPa.

3.2.3 Displacement Calibration

The displacement was measured at the crosshead, which is not the same as the displacement for the grip because there is a stretch of the different machine components primarily the load cell that is in between the grip and the crosshead. The stiffness of the system was measured by firmly connecting the upper and lower grip to each other. The inverse of the slope of the measured Force-displacement, ($\Delta L/\Delta F$), was then used to subtract the additional displacement due to straining of the load cell from the crosshead displacement to obtain the actual grip displacement.

$$Load\ compliance = \frac{\Delta L}{\Delta F} \qquad \textbf{(8)}$$

δ_{grip} = *the displacement of the grip (corrected displacement)*

$$\delta_{grip}(F) = \delta_{crosshead}(F) - \delta_{load\ cell}(F) \qquad \textbf{(8)}$$

$$\delta_{load\ cell}(F) = \frac{\Delta L}{\Delta F} \times F \qquad \textbf{(9)}$$

4 MATERIALS

Three types of materials were tested.
The isotropic hand sheets were made from a bleached and dried Scandinavian softwood Kraft pulp. The pulp was taken from SCA Östrand mill and refined to 3000 PFI revolutions. These hand sheets are labelled K40.
Grease proof paper for cooking and baking was used. The brand name for the grease proof paper used in the experiments is ‘Gourmanda Bak/Matlagnings paper’ manufactured by Metsä Tissue corporation in Finland. It is silicon treated and has an orthotropic material response.

An aluminium foil for wrapping food was also used. The brand name is ‘Glad Aluminium folie’ manufactured by Mellita Toppits in Finland. It is a homogeneous material with an orthotropic material response and it is slightly embossed.

4.1.1 Properties of the material

The measured thickness, grammage, density and friction coefficients of the materials are listed in Table 1 below.

Table 1: Density, thickness and grammage for the samples

(Average ± Standard deviation)

Material	*Density*	*Grammage*	*Thickness*	*Friction*	*Coefficient*
	Kg/m^3	*g/m^2*	*µm*	**Static**	**Kinetic**
K40	747	65±0.1	87±0.1	0.32	0.2
Grease proof	802	42±0.1	52±0.1	0.14	0.1
Aluminium foil	2141	36±0.1	17±0.1	0.32	0.2

5 EXPERIMENTS

The experiments involved zero, short and long span tensile tests using the two different tensile testers and three types of material as mentioned before. The acquired data was then used to investigate the effect of span length, thickness and clamping pressure on the material. The effect of slippage in the grips was also investigated by using materials having different friction coefficients. The zero span tensile tests were carried out on both the Pulmac Z-Span 2000 tensile tester and the MTS tensile tester.

Thickness by number of layers and clamping pressure was varied for all samples. The short span lengths were 200µm and 400µm on the Pulmac tensile tester while they were 400µm, 1000µm, 2000µm and 3000µm on the MTS tensile tester. The number of tests was 24 for Z-Span 2000 and 10 for the MTS tensile tester. However, the maximum span 1100µm in Z-Span 2000 and 4000µm in the MTS tensile tester were sometimes exceeded which reduced the number of valid tests for the longest span 400µm in Z-Span 2000 and 4000µm in the MTS tensile tester.

Apart from the aluminium foil, the papers are conditioned before testing. They are first placed in 30% relative humidity room for 24 hours then they are moved to a room with a constant climate of 23^{o}C and 50% relative humidity of where they remained throughout the tests.
The raw data collected from both machines after the experiments was evaluated using a Matlab code, which calculated the tensile properties and plotted the force-displacement curves with 20 data values.

6 RESULTS AND DISCUSSIONS

6.1 Long Span Tensile Test

A horizontal tensile tester by Lorentzen and Wettre is used to measure the stress-strain response of the samples using test method SCAN-P67:93 on 15 mm wide and 100mm long specimens. The data collected was only for the specimens that failed in the centre section or close to this section. The specimens failing in the region of the grips were discarded according to the test method. This failure behaviour can be attributed to the clamping pressure and the stress concentrations found near the region close to the grips [1]. During the tensile tests, aluminium foil showed a necking behaviour i.e. how the sample narrows down as it is stretched.

Figure 13: Stress-strain curves from the long span tensile test

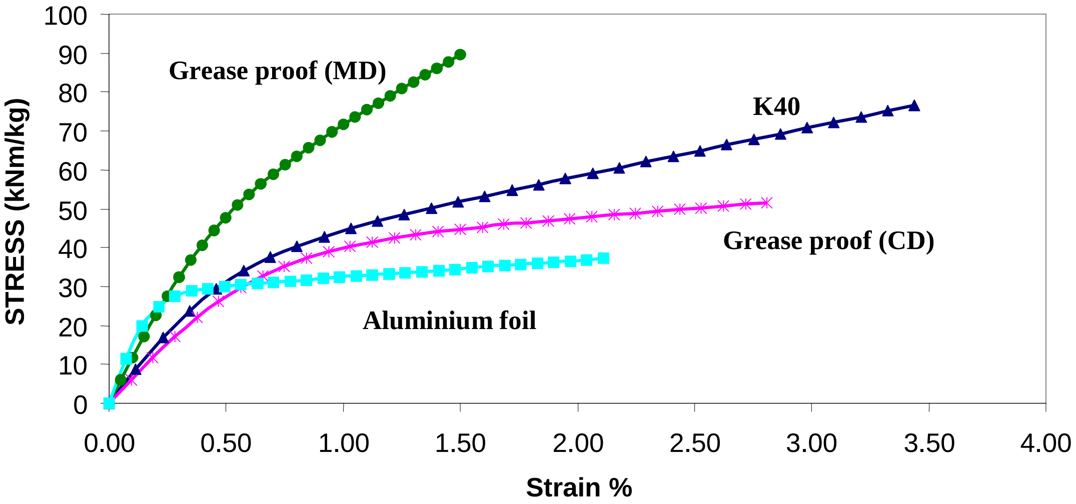


Table 2 : Mechanical properties of the samples using long span tensile test

Sample	*Strain At Peak %*	*Specific Stress At break kNm/kg*	*Tensile Energy Absorption Index J/kg*	*Tensile Stiffness Index MNm/kg*
Aluminium foil	2.11 ± 0.68	37.2±1.6	656 ± 276.9	17.18±1.35
Grease proof (MD)	1.50 ± 0.11	89.6 ±7.8	839 ± 133.1	11.8±0.81
Grease proof (CD)	2.81± 0.31	51.6 ±2.11	1094 ±162.8	6.47 ±0.33
K40	3.44 ± 0.12	76.6±1.06	1768 ± 79.3	7.73±0.20

From the LST table, Table 2 above, we see that the aluminium foil is the weakest material followed by grease proof in CD, K40 and the grease proof in MD is the strongest of all. The fracture of the aluminium foil and grease proof (CD) occurs along a straight line while for K40 and grease proof (MD) it occurs in a scattered criss-cross formation since they are stronger. This corresponds to the findings by Ranger et al [9] that for weak papers final fracture occurs along a single strain line while for strong papers, only short lengths of strain lines form in a widely scattered criss-cross formation. Although the grease proof in MD is the strongest, it has a low strain at break and hence a low tensile energy absorption index. This means in the MD direction, the grease proof is strong and brittle. On the other hand, in the CD direction, it is tougher because strain at break and TEA index is higher. Aluminium foil is both weaker and less ductile. Therefore among all four, the grease proof in CD and K40 have the highest stretching ability followed by the aluminium foil and lastly the grease proof in MD.

6.2 *Span Length*

6.2.1 Pulmac tensile tester

These tests were carried on the Pulmac tensile tester using a clamping pressure of 97.5MPa and specimens of width 22mm. The span length was varied for each sample tested.

The expected behaviour for the mechanical response when span length increases is that the tensile strength will decrease while displacement at break will increase. This is observed in grease proof in CD although the drop in tensile strength from 200 to 400 µm is very slight. The stress-displacement response for 200 and 400µm span is rather similar in the samples. Short span stress-displacement response exhibits a lower strength and a substantially higher displacement at break compared to ZST. This is as expected apart from the increase in stress for aluminium foil by three kNm/kg from zero to short span.

From Figure 14 below, we see only minor differences occur in the mechanical properties between the 200µm and 400µm SST especially for grease proof in MD and K40. However between the ZST and SST there are noticeable differences especially in regard to the displacement. Aluminium foil exhibits an increment of 50% in displacement, grease proof in MD and CD an approximate 24% increase and 13 % for K40.

In all four samples, the difference in tensile strength index (SI) between the zero span tensile test and the SST is small.

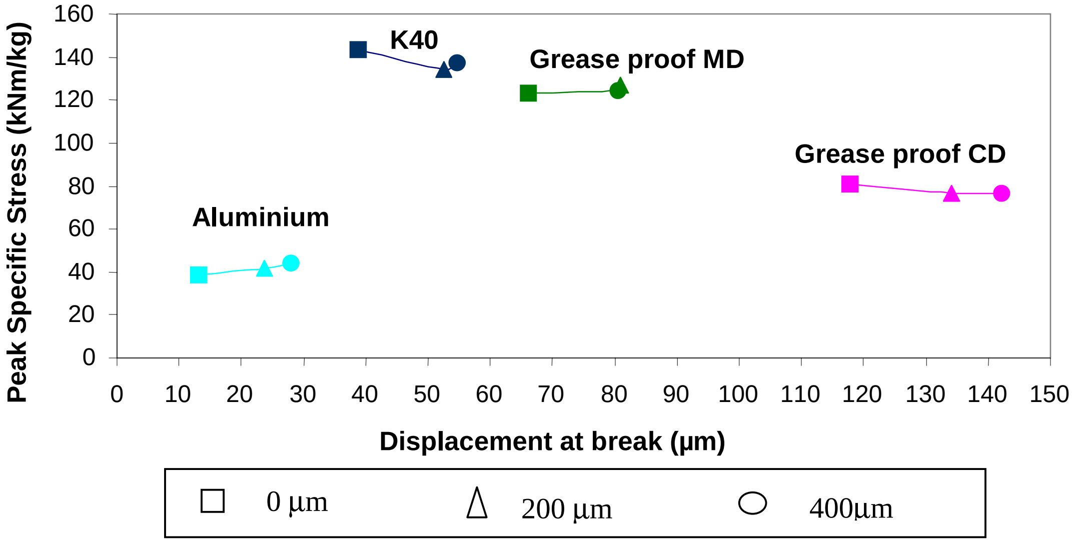


Figure 14: Effect of Span length on the stress-displacement response using the Pulmac device

6.2.2 MTS tensile tester

These tests were carried on the MTS tensile tester using a clamping pressure of 45.5MPa and specimens of width 15mm. The span length was varied for all tested samples.

From Figure 16 below, we see an increment in displacement with respect to increasing span length for all the materials. The grease proof in CD and aluminium exhibit the highest increase in displacement while a very slight or no difference in specific stress with increase in span length. This is because they both have more of a plastic yielding compared to grease proof in MD and K40. The increase in displacement at break is higher for shorter span lengths below 2000 and 1000 μm for aluminium foil and grease proof in CD respectively which is due to less slippage with increase in span length. For K40 and grease proof in MD the specific stress decreases with increased span length up to 1000μm and only a slight decrease occurs from a span length of 1000μm up to 3000μm.

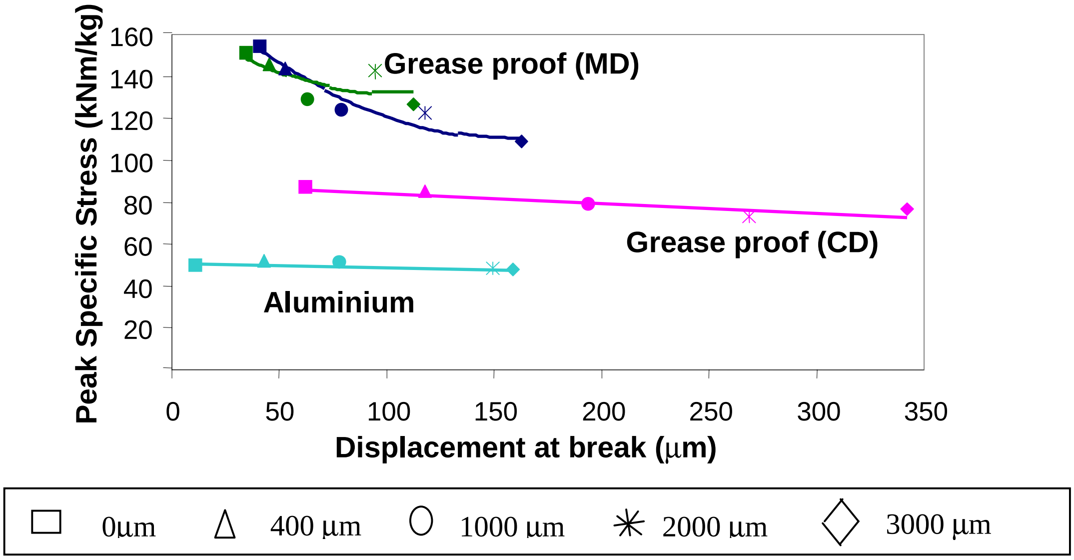


Figure 15: Effect of span length on the stress-displacement response using the MTS device

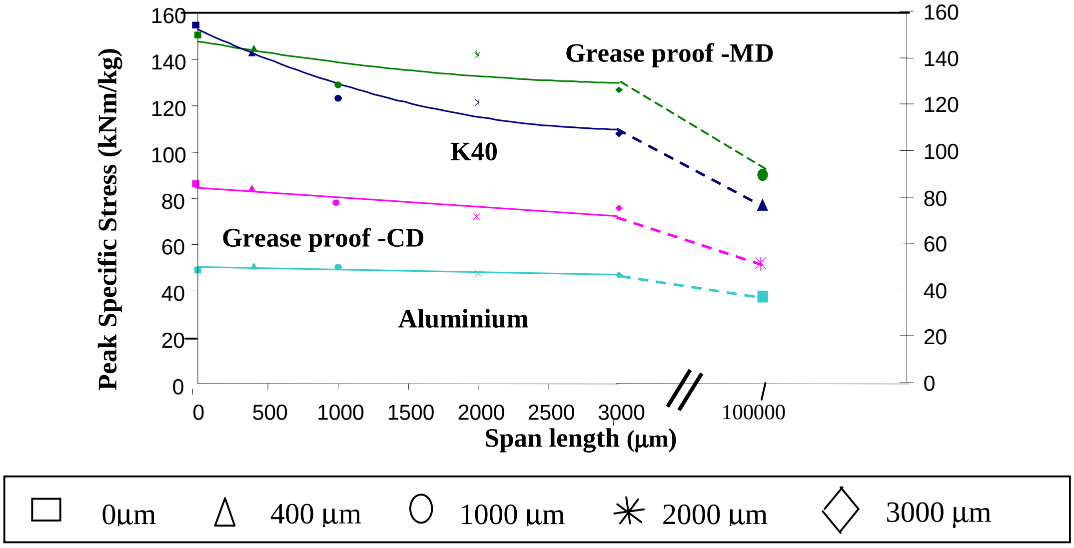


Figure 16: Effect of span length on the specific stress

Comparing the peak specific stress using the short spans and long span tensile test, we see from Figure 17 above that the specific stress remains constant or decreases slightly for aluminium foil and grease proof in CD at shorter span lengths but a 20% and 30% drop occurs between the ZST-strength and the LST-strength (100mm) respectively. As for K40 and grease proof in MD, there is a significant decrease in the specific stress at shorter span lengths and a drop of 30% between the ZST-strength and LST-strength.

6.3 *Clamping pressure*

6.3.1 Pulmac tensile tester

These tests were carried on the Pulmac tensile tester using the zero span tensile test method and specimens of width 22mm while using four clamping pressures.

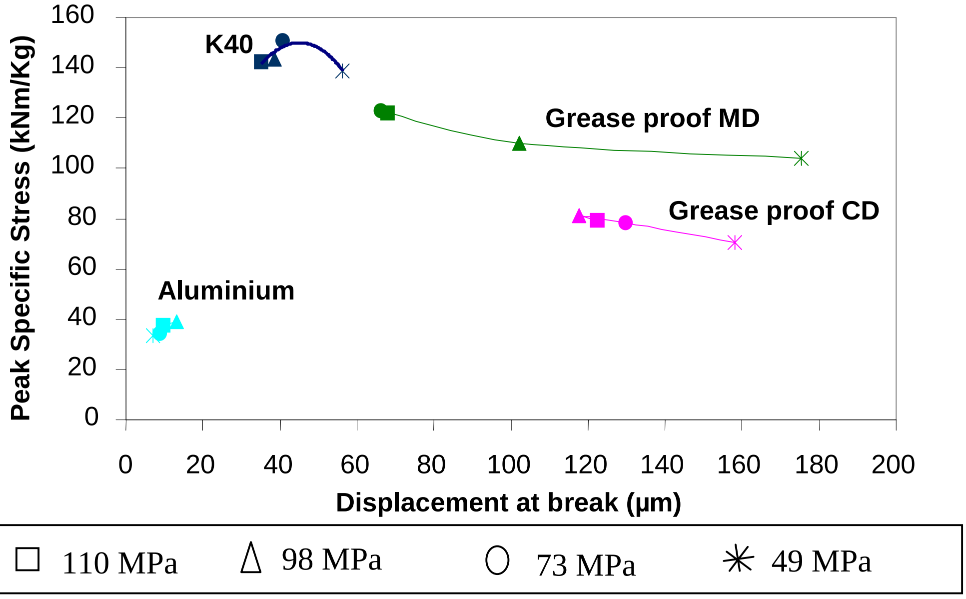


Figure 17: Effect of clamping pressure on the stress-displacement response using the Pulmac device

In Figure 18, we see that the clamping pressure does not affect the stress-displacement response for aluminium foil. Tensile strength index decreases with decreased clamping pressure for the paper samples and it is more pronounced for greaseproof in MD than in CD. Note that the tensile strength and displacement at break are almost the same for the two highest clamping pressures. Displacement at break increases for the paper samples with decreased clamping pressure and it is more pronounced for grease proof in MD than in CD. This can be explained by an increased slippage when the clamping pressure decreases.

6.3.2 MTS tensile tester

The range of clamping pressure 28.7, 45.5 and 53.8 MPa tested in MTS is lower than that of the Pulmac tensile tester. Normally, the clamping pressure used in the MTS is 45.5MPa which is less than half of the clamping pressure used in the Pulmac. 97.5MPa.

Figure 19 shows that stress increases with increasing clamping pressure. This behaviour may be explained by less slippage. Tensile stress will increase with clamping pressure due to more grip by the clamping jaws, which activates more fibres during tensile loading. K40 and grease proofs (MD) show a high increase in the specific stress of about 50% while grease proof (CD) and aluminium foil about 40% increase.

For all the four samples, the displacement at break decreases with increase in clamping pressure although not as much as the specific stress.

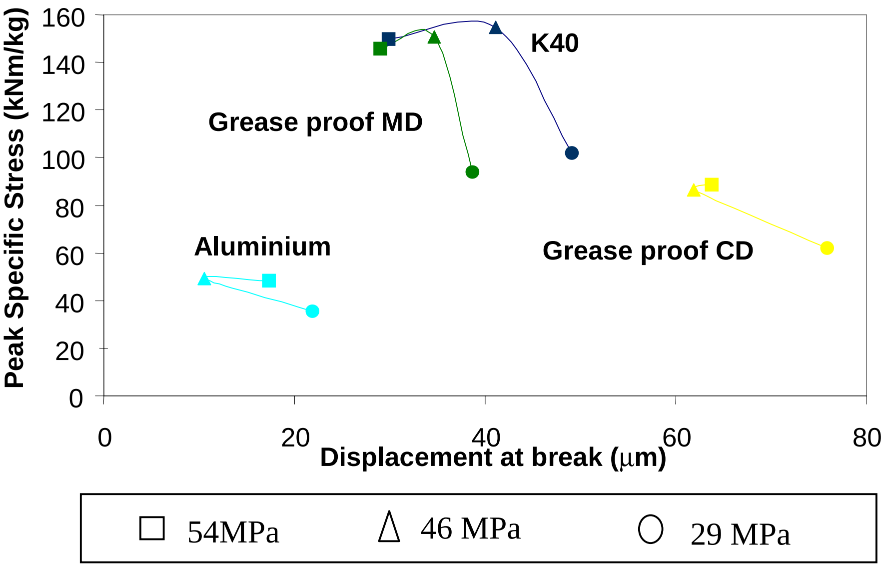


Figure 18: Effect of clamping pressure on the stress-displacement response using the MTS device

6.4 Thickness

Different numbers of layers were used to vary the thickness in a zero span tensile test using the MTS tensile tester with a clamping pressure of 45.5MPa. For paper samples, the individual sheets in an assembly of several layers did not break simultaneously. Instead a progressive failure occurred that started at the outer layers and moved towards the centre layer in the assembly. However, this was not observed for the aluminium sample where all individual layers broke simultaneously. For zero span tensile test, Figure 20, aluminium foil shows the effect of plastic deformation, which produces a uniform stress field through the sample. K40, grease proof in MD and CD experience an edge effect, which is a heterogeneous stress field with the highest stresses concentrated near the grips. Therefore the average specific stress will be higher in the thinner sample since it has flatter stress profile [13]. This is further shown by comparing to the results attained after testing the effect of thickness using the long span tensile test and the MTS loading frame, Figure 21. Note that the strain at break obtained when using the MTS frame is lower than with the L&W horizontal tensile tester used previously to obtain the LST results, Table 2.

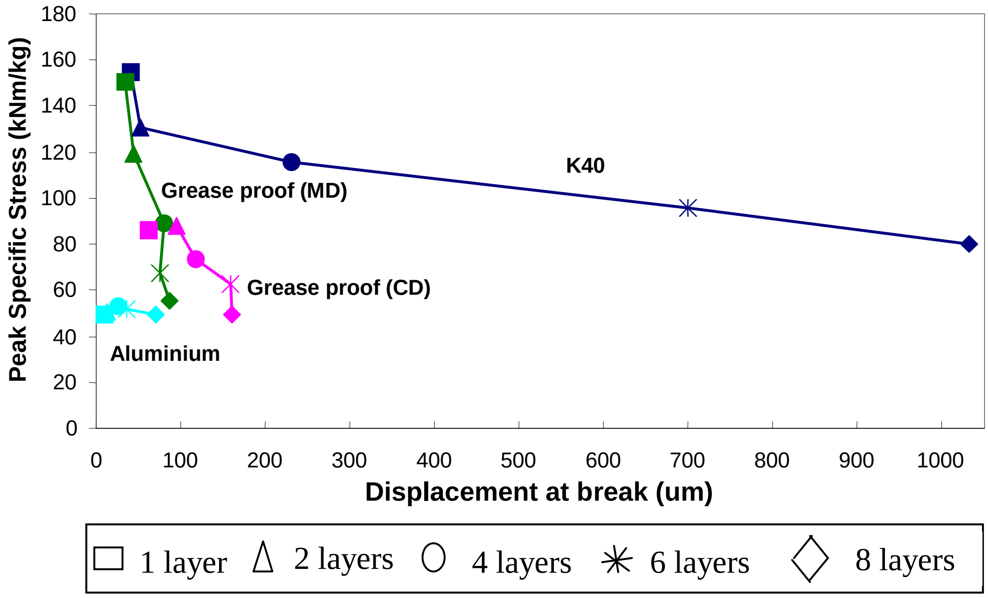


Figure 19: Effect of thickness on the stress-displacement response using Zero span tensile test

Displacement increases when thickness increases. This is because a higher thickness implies a higher load at break hence a higher slippage that contributes to the displacement causing a higher displacement. Also an error when compensating for displacements caused by the load cell can result in wrong calculated displacement measurements.

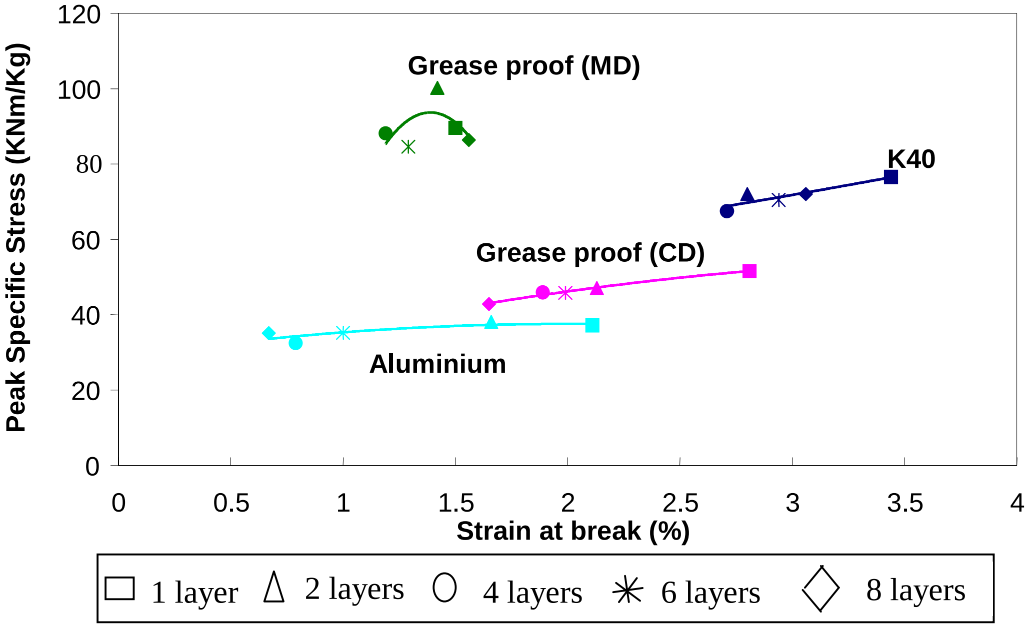


Figure 20: Effect of thickness on the stress-strain response using long span tensile test

6.5 Comparison of the Pulmac and MTS tensile tester

The results used to compare the Pulmac and MTS devices were for zero span and 400 µm short span tensile test since both tests were run on both devices. Mechanical properties for the materials compared are tensile strength, displacement and tensile stiffness (slope of the curve).

From Figure 23, we see load at break for aluminium foil, grease proof in MD and CD attained from the MTS device was 0 to 20% higher than for Pulmac. Tensile strength for K40 was the same for both devices using the zero span tensile test while for 400 µm SST the MTS tensile strength is 11% lower.

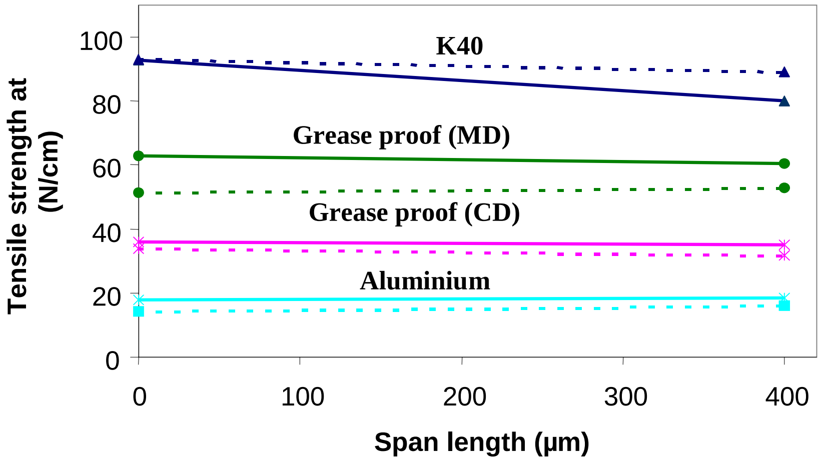


Figure 21: Tensile strength at break for Zero and 400um short span using the Pulmac (dotted lines) and MTS tensile testers (solid lines)

Figure 24 below shows that K40 has the same displacement at break independent of the measuring device and it is lower for zero span than for short span. Aluminium foil also had the same displacement at break in both MTS and Pulmac measured at zero span but is 50% higher at 400um span for the MTS device. For grease proof we see a difference in both MD and CD. The Pulmac displacement at break is double that of the MTS when using zero span while using short span the difference decreases to about 20%. In MD, the Pulmac displacement at break is also double the MTS displacement for both zero and short span.

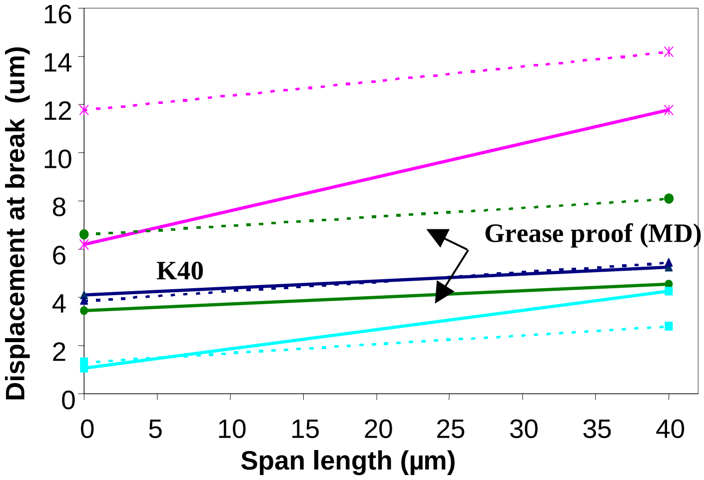


Figure 22: Displacement at break for Zero and 400um span using the Pulmac (dotted lines) and MTS tensile tester (solid lines)

Tensile stiffness decreases when span length increases as expected and the decrease is larger for the MTS tester compared to the Pulmac tester, Figure 25 below. Also, we see that the tensile stiffness is the same or higher when measured in the MTS tester instead of the Pulmac tester.

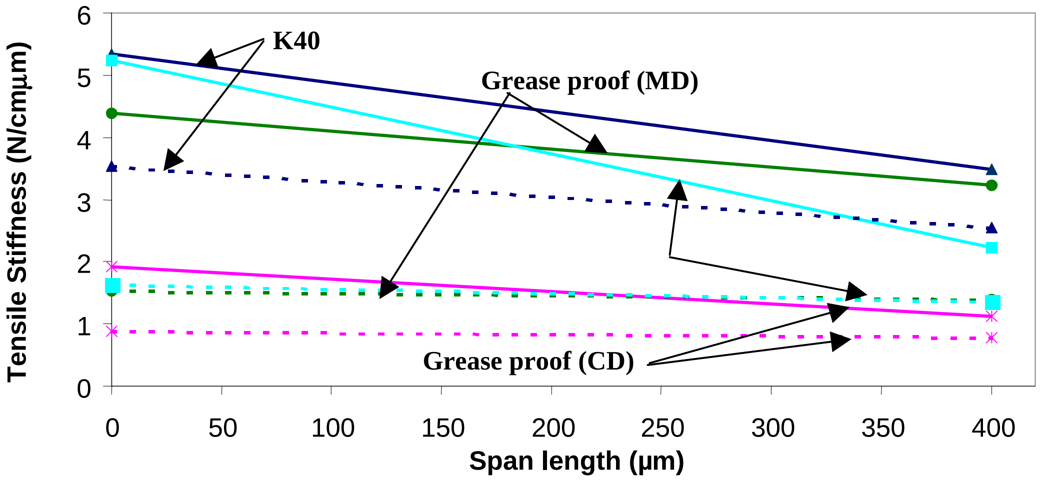


Figure 23: Tensile Stiffness at Zero and 400um short span measured in Pulmac (dotted lines) and MTS devices (solid lines)

7 CONCLUSIONS

The zero span and short span tensile strength of paper is sensitive to the stress fields, which depend on the plasticity of the material, thickness, span length and slippage.

Specific stress decreases with increased thickness for paper when using the zero and short span tensile tests. This is a result of edge or boundary effects where the stress field in the sample is concentrated to the region around the grips creating a non-uniform stress field through the sample. In the long span tensile test, the boundaries have no effect because of the high sample length to thickness ratio and thus the stress field is homogeneous through the thickness. As for aluminium foil, the stress field through the thickness remains homogeneous during both short span and long span tensile tests, which is due to the fact that it has no fibres.

Clamping pressure is important to consider for zero and short span tensile tests. A high thickness implies a higher load at break hence higher slippage and increasing the clamping pressure will reduce the slippage. The clamping pressure influences mainly displacement at break but too low clamping pressure will also give a lower zero span tensile strength.

As for the tensile testers, MTS device has some advantages over the Pulmac. The jaw teeth on the clamps for the MTS have a saw tooth design which makes them grip the sample firmer reducing the effect of slippage despite a lower clamping pressure than the Pulmac device. Also the clamps can be moved apart to a maximum distance of 5mm which allows running of different short span tests and testing materials with a high displacement at break. On the other hand, the MTS has a drawback in that it has no displacement gauge on the grips and a correction curve was used instead. The accuracy of this procedure has not been verified. The advantage of the Pulmac device over the MTS device is that it tests 24 specimens in one run, which saves time while the MTS only tests one specimen is for each run making it tedious and time consuming.

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9 APPENDICES

9.1 Appendix 1: MTS Tables

Table 3: Mechanical Properties after testing the effect of span length using the MTS device

Span Length um	*Tensile Strength index kNm/kg*	*Displacement at break um*	*Tensile stiffness N/cmμm*	*Tensile energy absorption N*
K40				
0	154.6±3.9	41.1±0.5	5.3±0.05	0.3±0.01
400	142.7±4.8	52.7±2	3.5±0.07	0.3±0.03
1000	123.1±5.9	79±3.5	2.3±0.17	0.4±0.01
2000	121.4±5.7	117.9±2.9	1.7±0.1	0.6±0.01
3000	107.8±3.9	162.9±4.5	1.2±0.03	0.8±0.05
Grease proof (MD)				
0	150.5±4.5	34.7±1.2	4.4±0.3	0.2±0.01
400	144.6±6.4	45.4±2.1	3.2±0.1	0.2±0.02
1000	129±5.7	63.1±2.7	2±0.1	0.2±0.02
2000	142±7.1	94.8±4.9	1.6±0.1	0.4±0.04
3000	126.8±5.6	112.2±1.5	1.2±0.1	0.4±0.02
Grease proof (CD)				
0	86.4±2.3	61.9±2.7	1.9±0.13	0.2±0.01
400	84.3±5.1	117.6±6.1	1.1±0.04	0.3±0.02
1000	78.1±5.5	193.9±5.8	0.6±0.03	0.5±0.04
2000	72.2±3.3	268.6±5.7	0.5±0.02	0.6±0.01
3000	75.7±3.7	342.1±3.9	0.4±0.04	0.8±0.04
Aluminium foil				
0	49.1±1.1	10.6±1	5.2±0.6	0.02±0.002
400	50.8±0.6	42.7±2.3	2.2±0.1	0.07±0.004
1000	50.4±0.7	78±3.5	1.3±0.1	0.12±0.007
2000	47.5±0.5	149.5±8.1	0.7±0.1	0.22±0.013
3000	47±0.8	158.7±5	0.7±0.04	0.24±0.01

Table 4: Mechanical properties after testing the effect of pressure using zero span tensile test on the MTS device

Clamping Pressure MPa	*Tensile Strength index kNm/kg*	*Displacement at break um*	*Tensile stiffness N/cmµm*	*Tensile energy absorption N*
K40				
28.9	102±3	49.1±2.4	4.2±0.3	0.24±0.02
45.5	154.6±3.9	41.1±0.5	5.3±0.1	0.28±0.01
53.8	149.8±2.6	29.9±0.3	8.3±0.6	0.21±0.01
Grease proof (MD)				
28.9	94±6.1	38.7±1.9	2.8±0.1	0.11±0.01
45.5	150.5±4.5	34.7±1.2	4.4±0.3	0.15±0.01
53.8	145.8±5.8	29±1.4	4.9±0.5	0.12±0.01
Grease proof (CD)				
28.9	62±2.9	75.9±5.5	1±0.1	0.14±0.01
45.5	86.4±2.3	61.9±2.7	1.9±0.1	0.16±0.01
53.8	88.7±1.5	63.8±4.2	1.6±0.2	0.17±0.01
Aluminium foil				
28.9	35.4±2.4	21.9±0.9	1.4±0.1	0.02±0.002
45.5	49.1±1.1	10.6±1	5.2±0.6	0.02±0.002
53.8	48.4±0.5	17.3±1.7	3±0.6	0.02±0.002

Table 5: Mechanical properties after testing the effect of thickness using zero span tensile test on the MTS device

No of Layers	***Thickness um***	***Tensile Strength index kNm/kg***	***Displacement at break um***	***Tensile stiffness Index kNm/kgμm***	***Tensile energy Absorption Index Nm^2/kg***
K40					
1	87	154.6±3.9	41.1±0.5	8.22±0.15	4.31±0.08
2	174	130.5±4.2	52.2±2.6	9.22±0.23	5.15±0.42
4	348	115.3±1.5	230.5±2	2.98±0.15	22.19±0.1
6	522	95.7±2.4	700.1±1.2	1.02±0.08	60.03±2.04
8	696	80.1±0.4	1032.4±5.8	0.62±0.04	74.81±4.47
Grease proof (MD)					
1	52	150.5±4.5	34.7±1.2	10.53±0.72	3.6±0.24
1	104	119±3.9	45±1.6	7.79±1.44	3.96±0.22
4	208	88.9±2.7	79.9±3.4	4.69±0.3	5.7±0.2
6	312	67.4±2.3	75±2.9	4.03±0.28	4.08±0.28
8	416	55.2±2.2	86.7±4.6	3.23±0.24	3.93±0.15
Grease proof (CD)					
1	52	86.4±2.3	61.9±2.7	4.6±0.24	3.84±0.17
2	104	87.9±4.9	94.9±5.6	2.87±0.12	5.88±0.59
4	208	73.6±1.3	117.3±7.1	2.22±0.12	6.24±0.41
6	312	62.5±1	158.2±9.1	1.71±0.08	7.75±0.49
8	416	49.2±1.1	160.1±8	1.44±0.09	6.32±0.43
Aluminium foil					
1	17	49.1±1.1	10.6±1	14.37±1.65	0.55±0.05
2	34	50.3±0.6	13.5±0.6	14.71±3.71	0.55±0.01
4	68	52.8±0.3	26.3±0.7	11.02±1.17	1.17±0.01
6	102	51.6±0.9	36.9±0.8	8.57±0.27	1.65±0.02
8	136	49.6±0.4	70.7±2.2	4.87±0.14	3.13±0.12

Table 6: Mechanical properties after testing the effect of thickness using the long span tensile test

No of Layers	*Thickness um*	*Tensile Strength index kNm/kg*	*Strain at break %*	*Tensile stiffness MNm/kg*	*Tensile energy absorption J/kg*
K40					
1	87	76.6±1.1	3.4±0.1	7.7±0.2	1768±79.3
2	174	72±2	2.8±0.2	7.5±0.1	1307±111.5
4	348	67.5±3.3	2.7±0.3	6.9±0.7	1151.7±170.8
6	522	70.5±4.3	2.9±0.1	6.7±0.7	1313.3±133.5
8	696	72±0.6	3.1±0.1	6.3±0.5	1384.1±29.7
grease proof(MD)					
1	52	89.6±7.8	1.5±0.1	11.8±0.8	839±133.1
2	104	100.2±6.3	1.4±0.1	13.6±1.4	842±143.6
4	208	88.2±5.6	1.2±0.1	12.6±1.3	561±111.8
6	312	84.6±3.6	1.3±0.2	11.2±1.5	580.9±151.4
8	416	86.4±4	1.6±0.1	9.7±1.3	727.4±93
grease proof(CD)					
1	52	51.6±2.1	2.8±0.3	6.5±0.3	1094±162.8
2	104	47±1.6	2.1±0.2	6.7±0.5	717.1±88.9
4	208	45.9±1.2	1.9±0.1	6.3±0.2	594.2±53.6
6	312	45.8±1.1	2±0.2	5.6±0.5	595.6±60.5
8	416	42.9±3.1	1.7±0.2	5.8±0.3	448.8±110.9
Aluminium foil					
1	17	37.2±0.1	2.1±0.68	17.2±1.4	656±276.9
2	34	38.1±1.9	1.7±0.03	12.7±2.8	503.49±25.3
4	68	32.5±1.3	0.8±0.04	7.1±3	109.22±30.4
6	102	35.2±1.4	1±0.03	7.5±2.2	200.05±42.5
8	136	35.1±1.5	0.7±0.1	13.3±1.3	148.71±48.4

9.2 Appendix 2: Pulmac Tables

Table 7: Mechanical Properties after testing the effect of span length using the Pulmac device

Span Length um	*Tensile Strength index kNm/kg*	*Displacement at break um*	*Tensile stiffness N/cmµm*	*Tensile energy absorption N*
K40				
0	143.3±6.3	38.8±3.4	3.5±0.3	0.22±0.03
200µm	134.8±8.8	52.1±3.7	2.6±0.3	0.28±0.04
400µm	137±6.6	54.6±4.2	2.5±0.3	0.3±0.03
Grease proof (MD)				
0	123±7.5	66.2±8.1	1.5±0.2	0.22±0.04
200µm	124.3±7.7	80.6±8	1.41±0.1	0.28±0.05
400µm	126.6±5.6	80.9±8.3	1.4±0.1	0.28±0.05
Grease proof (CD)				
0	81.2±5.1	117.9±6.8	0.9±0.1	0.26±0.02
200µm	76.8±5.6	134.1±9.7	0.7±0.1	0.28±0.04
400µm	76.3±7.6	142.1±16.1	0.8±0.1	0.31±0.06
Aluminium foil				
0	38.7±5.1	13.1±6.4	1.6±0.3	0.01±0.008
200µm	41.7±3.9	23.8±10.2	1.3±0.2	0.03±0.014
400µm	43.9±1.4	28±8.1	1.4±0.4	0.03±0.014

Table 8: Mechanical Properties after testing the effect of pressure using the Pulmac device

Clamping pressure MPa	*Tensile Strength index kNm/kg*	*Displacement at break um*	*Tensile stiffness N/cmµm*	*Tensile energy absorption N*
K40				
109.7	142.5±7.3	35.3±3.2	3.6±0.3	0.2±0.03
97.5	143.3±6.3	38.8±3.4	3.5±0.3	0.221±0.03
73.1	150.6±8.1	40.6±6.1	3.7±0.6	0.25±0.04
48.7	138.8±9	56.4±19.2	3.86±0.5	0.36±0.14
Grease proof (MD)				
109.7	122.2±6.5	68±7.2	1.4±0.1	0.22±0.04
97.5	123±7.5	66.2±8.1	1.5±0.2	0.22±0.04
73.1	110.1±8.2	102.1±18.9	1.43±0.1	0.34±0.09
48.7	103.7±9.1	175.4±39.7	1.2±0.1	0.56±0.17
Grease proof (CD)				
109.7	79.5±5.7	122.5±8.8	0.8±0.1	0.26±0.03
97.5	81.2±5.1	117.9±6.8	0.9±0.1	0.26±0.02
73.1	78.5±3.4	129.6±10.7	0.9±0.08	0.28±0.03
48.7	70.3±5.3	158.2±19.7	0.8±0.1	0.33±0.06
Aluminium foil				
109.7	37.4±7.3	9.7±3.7	1.8±0.5	0.01±0.004
97.5	38.7±5.1	13.1±6.4	1.6±0.3	0.01±0.008
73.1	34.3±8.4	8.8±3.3	1.7±0.5	0.01±0.004
48.7	33.5±6.5	7.1±2.6	1.9±0.3	0.005±0.003

10 LIST OF FIGURES AND TABLES

10.1 Figures

10.2 Tables