Study of Creep Characteristics of Multi-layered Corrugated Fibre Board Protective Cushions

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2011

A thesis submitted in fulfilment of the requirement of the Degree of Masters by Research

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Abstract

Multi-layered corrugated fibreboard, has in recent years been gaining attention as a replacement for polymeric materials for protective packaging for environmental reasons. The properties of pre-compressed multi-layered corrugated fibreboard make it a sustainable replacement for poly-foam and polystyrene. Pre-compressed multi-layered fibreboard cushions have most of the structural resistance and damping removed, they behave more like a soft spring. The performance of pre-compressed multi-layered corrugated fibreboard as a protective cushion is influenced by the amount of moisture present. The material stiffness is also dependent on the amount of moisture present. Static compression testing can be carried out to obtain stiffness data by measuring load versus controlled deflection, with stiffness being the load required to deflect a specified distance. The creep properties can be obtained by measuring deflection with a controlled force over a period of time, that is, creep is a measure of deflection per time under a constant force.

Models can be developed to simulate creep data, the Voigt model of Visco-elasticity, a spring – damper model makes a reasonable choice of model. This model is an exponentially decaying expression that can be adapted with respect to static strain, stress or stiffness and can be fitted to creep data. Curve fitting with a non-linear optimisation technique shows the model has a reasonable fit with experimental data. Creep data and curve fitting shows an unexpected trend in that as the humidity level is raised the creep strain levels reduce. The effect of this is offset by higher static strains occurring at higher humidity levels. At higher humidity levels when using the exponential model the creep strain reaches the 63% of total strain quicker than at lower humidity levels.

The new models from this research will help better predict the effects of current and new paper corrugated materials for packaging applications, when exposed to high humidity and long term storage such as in a tropical warehouse.

Student Declaration

"I, Hussein Mahanny Shehab, declare that the Master Degree thesis entitled

Study of Creep Characteristics of Multi-layered Corrugated Fibre Board

is no more than 60,000 words in length, exclusive of tables, figures, appendices, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature Date

Acknowledgements

The author would like to acknowledge guidance and encouragement given by his principal supervisor Dr Merv Minett.

The author would also like to thank his Co-Supervisor Prof Graham Thorpe and the technical staff of the School of Engineering and Science.

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Chapter 1 Introduction

There have been many materials used in the protective packaging area over many decades, such as expanded polystyrene (EPS) and Poly-foams. These materials have been difficult to re-cycle and generally end up in landfill. Paper based materials tend to be more amenable to re-cycling, although more expensive to manufacture. Corrugated fibreboard has been used in the packaging industry for many years mainly as containers and boxes to pack goods for transportation. This material has however can also be used as protective cushions inside containers usually constructed in multiple layers

Pre-compressed multi-layered corrugated fibreboard cushions, which is the essence of this study, consists of layers of virgin board glued together then compressed to remove the rigidity and to create a spring like structure. The virgin board usually consists of corrugated fibreboard sheet sandwiched between two plain sheets as shown in Figure 1.1

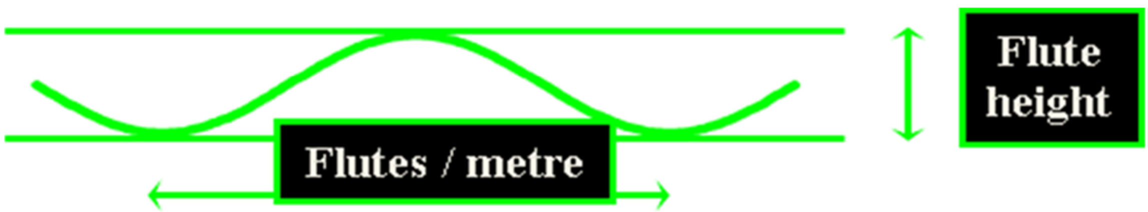

Figure 1.1 Corrugated Fibreboard Flute

The flute configuration can be of the following sizes as shown in Table 1-1 with the size shown in yellow being a commonly used size in cushioning.

Table 1-1 Tabulation of corrugated fibreboard sizes

Flute type	Flute height (mm)	Flutes per metre	Average medium take-up factor	Flat compr.	Cross-direction compr.
A	4.70	110	1.54	100%	100%
C	3.61	129	1.45	125%	85%
B	2.46	154	1.33	150%	75%
E	1.14	295	1.26	350%	60%

It is felt that the pre-compressed corrugated fibreboard is a good substitute for polymeric materials such as poly-foams and EPS which are commonly used in the packaging industry.

As with all cushioning materials it is necessary to determine the cushioning characteristics prior to using as a protective cushion. Within the dynamics and vibrations research group at Victoria University and elsewhere much research has been carried out into the application of virgin and pre-compressed multi-layered corrugated fibreboard cushions for protective packaging in storage and delivery containers boxes. The main focus has been on the shock attenuation or cushioning characteristics, methods to produce cushion curves using simple compression data and modeling of cushion dynamic behavior and producing records such as impact failure as shown in Figure 1.2.

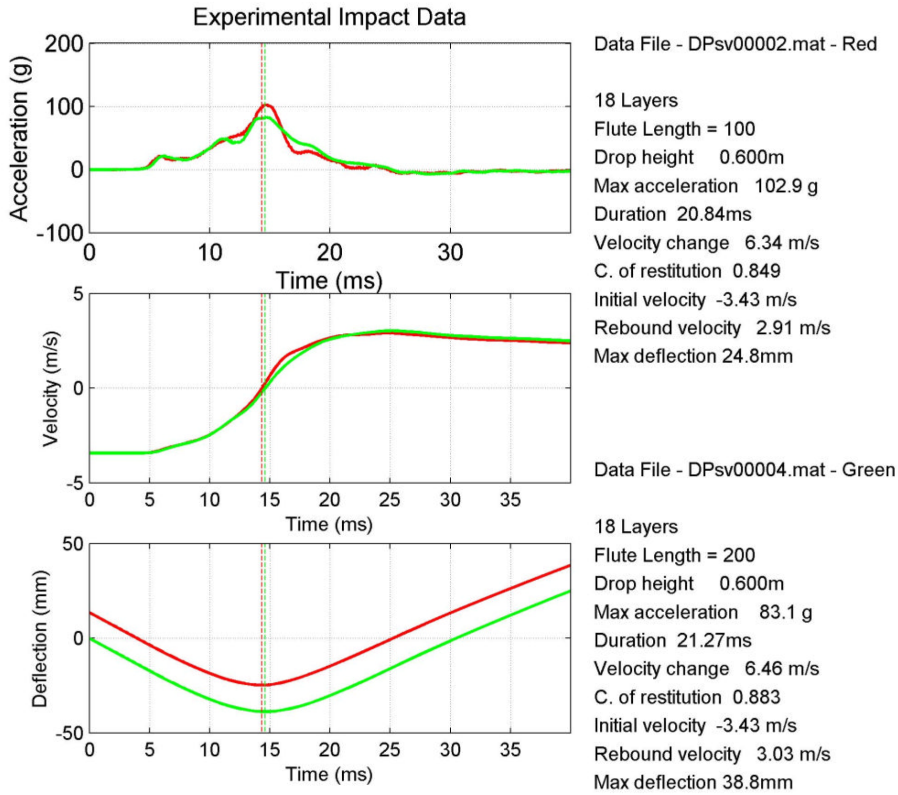

Figure 1.2 Impact Behaviour of Pre-compressed Multilayered Fibreboard

Another dimension to cushion testing is to take into account that when packaged products are in stored in boxes for longer lengths of time, such as in storage, there is a tendency for protective cushions to experience creep or time dependent deformation. The protective cushions lose thickness that leads to a slackening off to the interface between the cushion and the packaged product. This would create direct deterioration of the cushioning effect or loss of support during impact or vibration, and subsequently lead to product damage.

One method to overcome this is to allow more cushioning, but to establish how much, requires some knowledge of the creep behaviour.

As this product is a paper product there is also the question of humidity affects the creep performance. There has been work produced on the creep behaviour of corrugated fibreboard storage boxes particularly with respect to the effect of humidity. However there seems to be little work on the creep behaviour of corrugated fibreboard protective cushions, especially when the cushions are pre-compressed. There is then a need to study Creep Behaviour of Pre-compressed Corrugated Fibreboard protective cushions. The pre-compression process reveals knowledge of the static compression characteristics of the material which is an adjunct to the creep process.

The work for this study is described in the following chapters:

The literature review in chapter two talks discusses static compression and creep in corrugated fibreboard and proposes the methodology for this study.

Chapter three describes static compression and creep testing procedure.

Chapter four provides the analysis of the experimental results and modelling processes.

Chapter five contains discussion and main conclusions.

Chapter 2 Literature Review

2.1 Static Pre-compression

Like all materials for pre-compressed multilayered corrugated fibreboard cushions to be used as protective cushions the mechanical actions need to be determined. As stated in the introduction one such action is creep, or time dependent deformation, and is the ultimate purpose of this study. Before discussing creep actions some understanding of pre-compression is required. As the name pre-compressed suggests multi-layers of corrugated board are compressed or crushed so as to take out some of the structural stiffness of the structure, this creates a spring like structure similar to polymeric materials. Although this part of the discussion is not directly a part of creep behaviour it will form part of the experimental procedure in respect to the cushion preparation so it is therefore worthwhile including.

Authors have studied this procedure and attempts have been made to create models. Minett, M. W. (2005) introduced a model that simulated the elastic, visco-elastic and crushing phases of pre-compressing multi-layered corrugated fibreboard. The model is shown in Equation (2.1). This theory was based on work carried out on poly-foam protective cushions by Thakur, K. and McDougall, A. (1996). Phase one (P1) is the stiffer and semi-linear section at the beginning of the stress-deflection curve. The second phase (P2) is a softer more fluid phase or visco-elastic phase. By introducing a periodic phase (P3) it was possible to describe the compressive behaviour of multi-layered corrugated fibreboard whilst being crushed.

$$P1 = F_m\left(1 - e^{-a\varepsilon}\right) \quad \text{Phase 1 Semi-Elastic}$$

$$P2 = SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right) \quad \text{Phase 2 Visco-Elastic}$$

$$P3 = F_a \cos(2N\pi y / b) \quad \text{Periodic Phase}$$

$$F = P1 + P2 + P3$$

Therefore

$$F = F_m\left(1 - e^{-a\varepsilon}\right) + SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right) + F_a \cos(2N\pi y / b)$$

where

$F =$ the instantaneous force

$F_m =$ the mean force

$F_a =$ the alternating force

$SF =$ the slope factor

$N =$ the number of cushion layers (2.1)

$y =$ the displacement record

$\varepsilon =$ the strain - the ratio of deflection to unloaded thickness

$\varepsilon_0 =$ the maximum strain

b is a multiplier

Minett and Sek (2000) offered an explanation into how corrugated fibreboard will collapse during static compression. Individual layers do not necessarily collapse at the same time. They tend to roll over at a particular time followed by another layer at random intervals. These observed effects lead to the hypothesis that the fluctuating section of the compression is due to the intrinsic behaviour of the individual layers of a multi-layered configuration of a cushion pad made from corrugated fibreboard.

The authors also suggested the following model to understand the buckling or collapsing effects. The model is that the behaviour can be described by considering compression springs in series and compressed. Each spring represents a layer in the cushion pad. The springs interact with each other in an elastic manner or failure due to visco-elasticity as shown in Figure 2.1

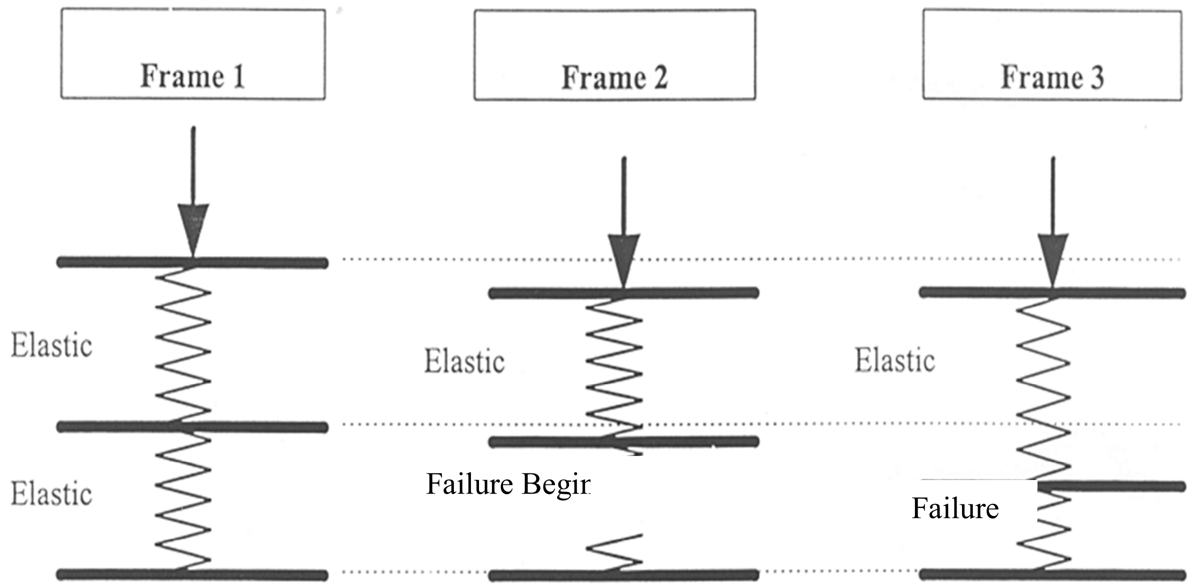

Figure 2.1 Spring model representing two layers of corrugated fibreboard

The first frame shows that the springs are under elastic deformation and the total deflection is the addition of the individual deflections. The second frame shows that the bottom spring has begun to fail (negative stiffness) and the spring offers no further resistance. The top spring will then expand as the force on the bottom spring is relaxed and the total deflection is dependent on the force in the bottom spring. Frame three shows the top spring expanding thus retaining its elastic behaviour. To understand the implications of this behaviour, the authors proposed a simple configuration of two linear springs in series subject to compression load and constructed as shown in Figure 2.2. The figure also shows compression characteristics of two springs a gradually increasing force is applied from O to point A the two springs are behaving in a linear fashion, thus the force and deflection of the system can be described by the following equation.

$$\begin{aligned} &\text{Deflection} \quad x = x_1 + x_2 \\ &\text{and} \\ &\text{Force} \quad F = F_1 = F_2 \end{aligned} \tag{2.2}$$

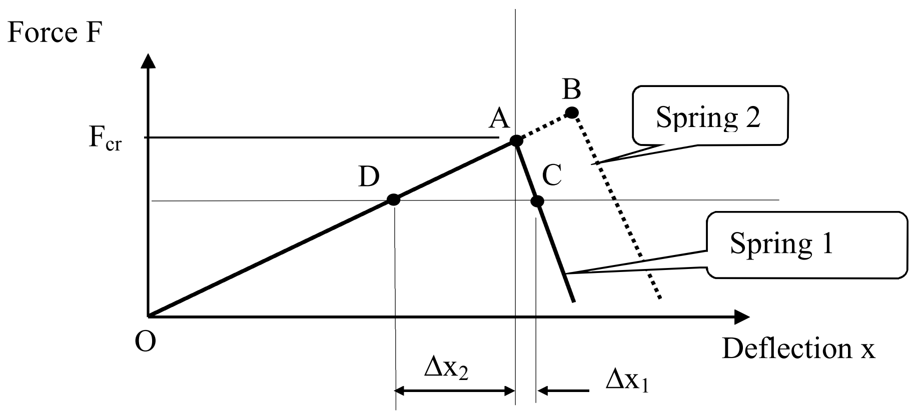

Figure 2.2 Representation of two springs compressed to failure

When the deformation reaches point A spring 1 starts to fail and its deformation requires less force. This spring is now independent and non-linear behaviour begins due to visco-elastic failure. Because there is equal force on both springs and as they are in series, then theoretically the spring 1 will continue to deform by Δx_1 and spring 2 will expand by Δx_2, to match the force of the independent spring, the total deflection is reduced. This will continue until spring 1 is completely bottomed and spring 2 will begin to deform again with increasing deflection and force.

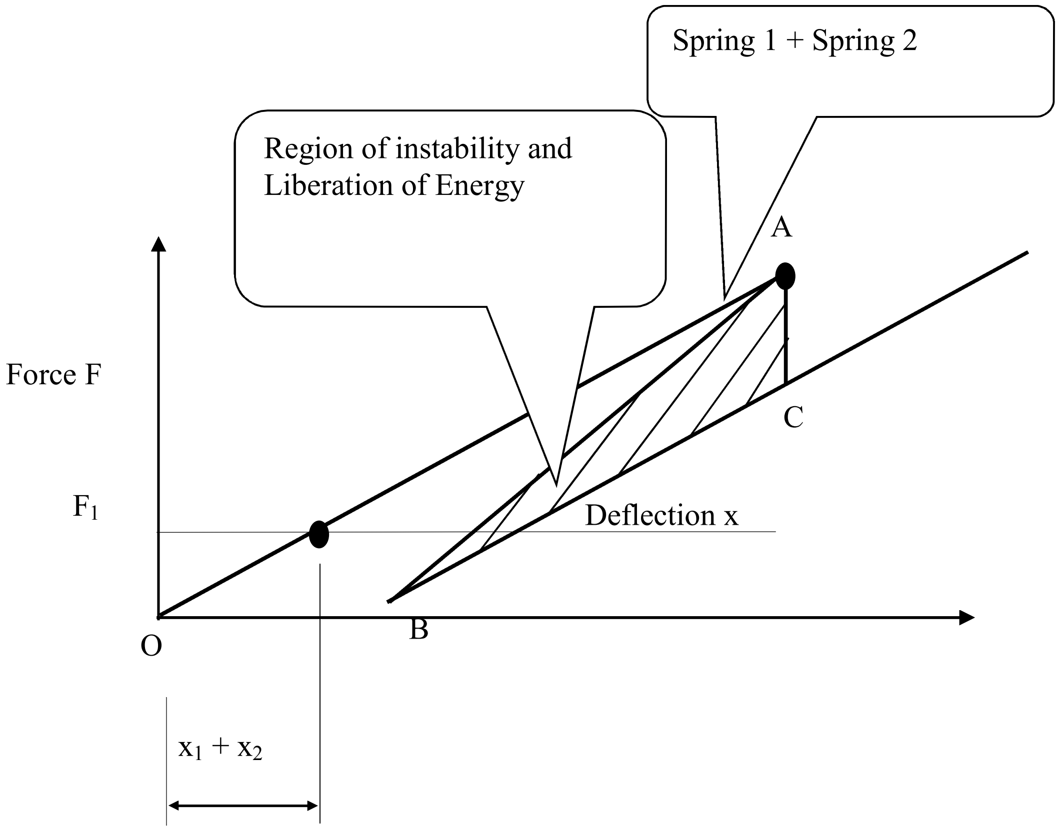

Figure 2.3 The resulting Force v Deflection after failure of spring 1

Figure 2.3 shows the resulting diagram of force versus deflection. Experimentally the overall deflection cannot diminish as the springs are locked between press platens and the shaded section in

Figure 2.3 A, B, C area becomes a region of instability. The force will therefore decrease in an instant to a lower force at point C, in other words energy has been liberated and the springs try to find equilibrium in an instant and a fluctuation is produced. This process would be repeated, if more springs (pad layers) were added.

The preceding discussions are not so much about creep mechanisms; however it gives some insight on how the pre-compressing process works.

2.2. Creep Considerations

Creep or time dependent deformation is generally thought to be the greatest at the initial loading and then declines in some exponential way over a further period of time.

Mathematical models can be formulated to represent creep mechanisms such as that suggested for packaging use by Mustin (1968). Mustin suggested that the Voigt Solid model gives good results for polymeric materials. The Voigt model is made up of a linear spring in parallel with a dashpot shown in Figure 2.4.

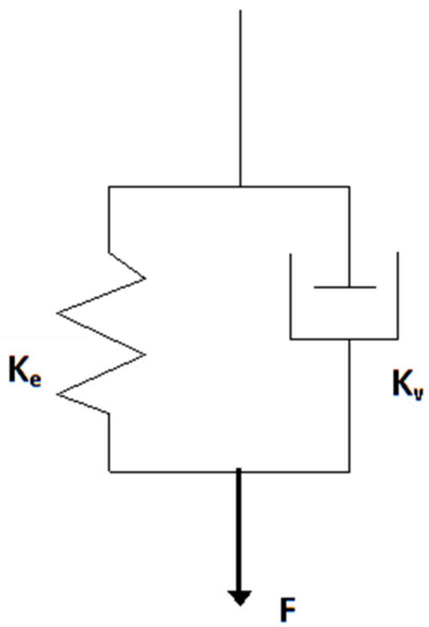

Figure 2.4 Voigt Model of Viscoelasticity

Mathematically the Voigt model can be described by Equation (2.3).

$$\begin{aligned}&F = k_e x_t + k_v (dx/dt)\\&\text{where F is the applied force in N}\\&k_e \text{ is the spring stiffness in N/m}\\&k_v \text{ is dashpot constant in Ns/m}\\&\text{t is time over an interval in secs}\\&x_t \text{ is the displacement in time t}\end{aligned} \qquad (2.3)$$

This equation can be re-arranged such that it is variable separable and can easily be integrated to determine the deflection x_t under the force F. After re-arranging equation (2.3) becomes

$$(k_e/k_v)dt = dx\Big/\big[(F/k_e) - x\big] \qquad (2.4)$$

And integrating both sides leaving the subscript t off for convenience

$$\begin{aligned}&(k_e/k_v)t = -\ln\big[(F/k_e) - x\big] + c\\&x = 0 \text{ at } t = 0 \text{ which means } c = \ln(F/k_e)\\&\text{therefore by substitution of C}\\&-(k_e/k_v)t = \ln\big[(F/k_e) - x\big] - \ln(F/k_e)\\&\text{by use of logarithmic rules}\\&-(k_e/k_v)t = \ln(1 - xk_e/F)\\&\text{therefore by taking exp both sides}\\&\text{and putting x in terms of time t yields}\end{aligned}$$

$$x_t = \frac{k_e}{F}\left(1 - \exp\left(\frac{-k_e t}{k_v}\right)\right) \qquad (2.5)$$

By definition

$$x_t = \frac{F}{L_o}$$

L_o is the original length and

$$\tau = \frac{k_v}{k_e}$$

where τ is a relaxation time or
time strain reaches approx 63% of the
final state

$$\varepsilon_t = \varepsilon_\infty \left[1 - \exp\left(-t/\tau\right)\right] \tag{2.6}$$

where
ε_t is the strain at time t
ε_∞ is the final strain

Some other empirical expressions that can describe the strain-time relationship (creep) are:

$$\varepsilon = \varepsilon_i\left(1 + \beta t^{1/3}\right)\exp\left(kt\right) \tag{2.7}$$

where ε_i is the initial (or static) strain
β is a constant for transient creep
t is time over an interval in secs
and k is related to the constant strain rate

A better fit is obtained by:

$$\varepsilon = \varepsilon_i + \varepsilon_t\left(1-\exp\left(rt\right)\right) + t\dot{\varepsilon}_{ss}$$

where r is a constant
ε_t is the strain at the transition
from primary to secondary creep (2.8)
$\dot{\varepsilon}_{ss}$ is the steady state strain rate
ε_i is the initial (or static) strain
t is time over an interval in secs

General forms of nonlinear strain-time relations have been developed, one such relationship is

$$\varepsilon = \varepsilon_i + B\sigma^m t + D\sigma^\alpha\left(1-\exp\left(-\beta t\right)\right)$$

t is the time over an interval in secs (2.9)
σ is the static stress in pa
and are B, m, D, α and β are empirical constants

Equations 2.7 to 2.9 were used by Minett and Shehab (2008) to model creep in corrugated fibreboard with some success, however these are generally used for creep in metals and are not really suitable so will be ignored in this study.

Equations 2.4 to 2.6 require that the static or initial strain ε_i be known so after pre-compression static stiffness can be obtained by compressing and measuring load versus deflection. This is a common procedure used for most material properties. The slope of straight line section of the following typical graph will determine the Static Stiffness.

As stated in the introduction protective cushions with a higher stiffness values are better equipped to resist creep.

Pre-compressed multilayered corrugated fibreboard is a paper product and could be more susceptible to creep under conditions of higher humidity. How moisture levels are integrated to the behaviour of corrugated fibreboard boxes has been studied by various authors.

Byrd, N. L. (1972) analysed tensile and compressive creep behaviour of single layers of corrugated fibreboard in two different ways namely constant humidity and cycle humidity. At equal creep loads it was determined that specimens tested in cyclic humidity environments had higher creep rates than those in constant humidity environments. It is possible that cyclic humidity will cause lower material stiffness and thus higher creep providing the cyclic base is at the higher levels of humidity for multilayered corrugated fibreboard. Soremark and Fellers (1992) tested the characteristics of bending paperboard in a constant humidity and cyclic humidity environments. The authors found that compression will increase hygroexpansion and tension decreases it. Hygroexpansion being the swelling and shrinking that occurs with changes to the relative humidity.

Multilayered pre-compressed protective cushions would mainly be exposed to compression, therefore Soremark and Fellers findings may be an important consideration. On the other hand multilayered corrugated board may not be affected as much by cyclic humidity due to hygroexpansion because of multi-layered construction, in particular the pre-compressed type which has small layer heights. The amount of moisture at the surface of the cushion will be more pronounced than inside, particularly if the cushion is fitted tightly within a box or has blocked ends. Research by Habeger and Coffin (2000) suggested that a physical explanation for accelerated creep consists of two interconnected events that occur during creep in cyclic humidity. The first observation in that the total deformation under the action of a cyclic load is greater than the creep due to the application of the mean load. The second is that changes in moisture content give rise to stress gradients (not a uniform distribution of the dead load). During creep in cyclic humidity the stress at any given point will be cycling. The overloaded regions contribute more to creep than that which is suppressed by the under-loaded regions. The net effect is an acceleration of creep during and for some time after a change in moisture. Alfthan, J, (2004) discussed the effect of the change in moisture content, or more specifically varying amplitudes of moisture content (moisture cycling). When the material is loaded there is a cumulative ratcheting up of deformation following each increase of moisture content, which is known as mechano-sorptive creep.

The research by Alfthan was based on single layered corrugated fibreboard, however the ideas could hold credence for the pre-compressed multi-layered fibreboard cushions. Under load, creep might be exacerbated at varying elevated moisture levels and humid conditions and cause cumulative increases of deformation.

One impediment to these thoughts is the time taken for full moisture absorption within multi-layered fibreboard cushions. This material is fairly tightly packed in the pre-compressed state and could have a resistance to moisture absorption. These moisture absorption rates will need to be experimentally determined to test this theory.

It should be possible if data at known levels of moisture content are known, to simulate what would occur if pre-compressed multi-layered fibreboard cushions were subjected to different moisture levels. Some typical humidity levels for Melbourne are shown in Figure 2.5. The range is between 60 and 80% humidity. As packages are mainly stored internally, humidity levels lower than 6o% can be considered.

Graphical climate statistics for Australian locations Page 1 of 2

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Climate statistics for Australian locations

Monthly climate statistics - graph

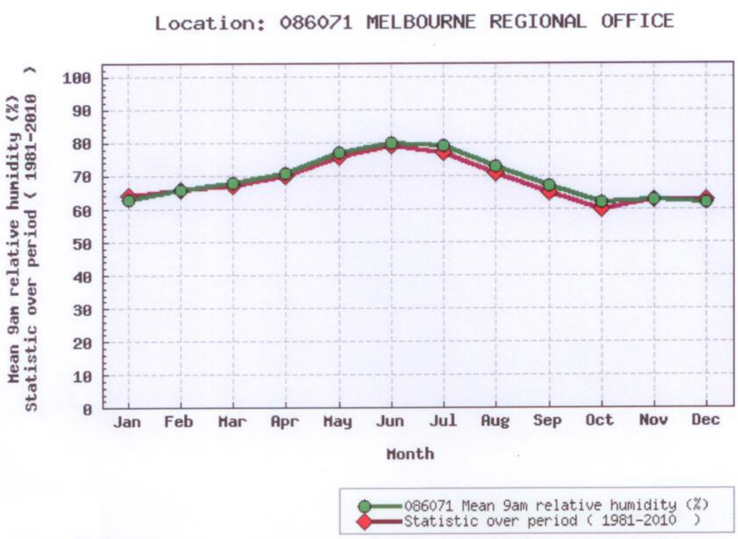
MELBOURNE REGIONAL OFFICE

Mean 9am relative humidity (%)

Site details

Site name: MELBOURNE REGIONAL OFFICE **Site number:** 086071 **Commenced:** 1908

Latitude: 37.81 °S **Longitude:** 144.97 °E **Elevation:** 31 m **Operational status:** Still Open



Australian Government
Bureau of Meteorology

Created on Tue 7 Dec 2010 15:57 PM EST

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years
Mean 9am relative humidity (%) for years 1955 to 2010	63	66	68	71	77	80	79	73	67	62	63	62	69	56
Statistics	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Years**
Mean 9am relative humidity (%) for years 1981 to 2010	64	66	67	70	76	79	77	71	65	60	63	63	68	30

Additional information

Related Links

- Summary statistics and locational map for this site: http://www.bom.gov.au/climate/averages/tables/cw_086071.shtml
- About climate averages: http://www.bom.gov.au/climate/cdo/about/about-stats.shtml
- Definitions of the individual statistical elements: http://www.bom.gov.au/climate/averages/tables/definitions.shtml

http://www.bom.gov.au/jsp/ncc/cdio/cvg/av 7/12/2010

Figure 2.5 Typical Relative Humidity Chart for Melbourne

Protective cushions with a higher stiffness values are better equipped to resist creep, stiffness being the load required for deflection. The stiffness of paper products is affected by moisture or humidity levels. How moisture levels are integrated to the behaviour of corrugated fibreboard boxes has been studied by various authors, but not so with respect to multi-layered corrugated fibreboard.

2.3 Methodology

The previous discussion forms the basis of the project aim and the methodology that follows.

The questions posed for this study of the creep characteristics at varying humidity levels of multi-layered corrugated fibreboard protective are:

1. What are the cushion static compression characteristics?
2. When subjected to axial load will the cushions suffer time dependent deformation (creep)?
3. If creep is evident can it be modeled with, or some variation of, the Voigt Model of Viscoelasticity?
4. What are the experimental constants when fitting the Voigt model?
5. Can a family of cushion curves be established?

Chapter 3 Experimental Work

3.1. Introduction to Experimental Work

As suggested in Chapter 2 experimental strain data taken from creep testing of pre-compressed multi–layered corrugated fibreboard cushions may be fitted to models to provide an analysis into how they may perform in various environments. The following Voigt creep model, Equation (3.1) suggested in Chapter 2, determines the strain ε_t and is a function of the final strain, which is not necessarily known. However it could be determined using the initial strain or static strain. Initial strain can be determined experimentally either from static compression testing or from initial loading within a creep test.

$$\varepsilon_t = \varepsilon_\infty \left[1 - \exp\left(-t/\tau\right)\right] \tag{3.1}$$

where

ε_t is the strain at time t

ε_∞ is the final strain

This concept of using the Voigt model with initial strain rather than the final strain is developed in Chapter 4 using the experimental data described in the rest of this chapter.

3.2. Cushion Crushing

In order for multi–layered corrugated fibreboard cushions to become pre-compressed they need to be crushed to mostly remove the structural stiffness and create a spring structure. This work was carried out on a number of cushions made of multi–layered pre-compressed corrugated fibreboard consisting of 10 layers and 75mm square. The cushions were constructed with layers of virgin 'C' flute corrugated board with liners on both sides. To obtain pre-compression the samples were crushed using the Lloyd universal tensile testing machine. Nexygen data acquisition software was used to record data. The Lloyd tensile testing machine is a power screw operated device that measures applied force with a load cell against controlled deflection.

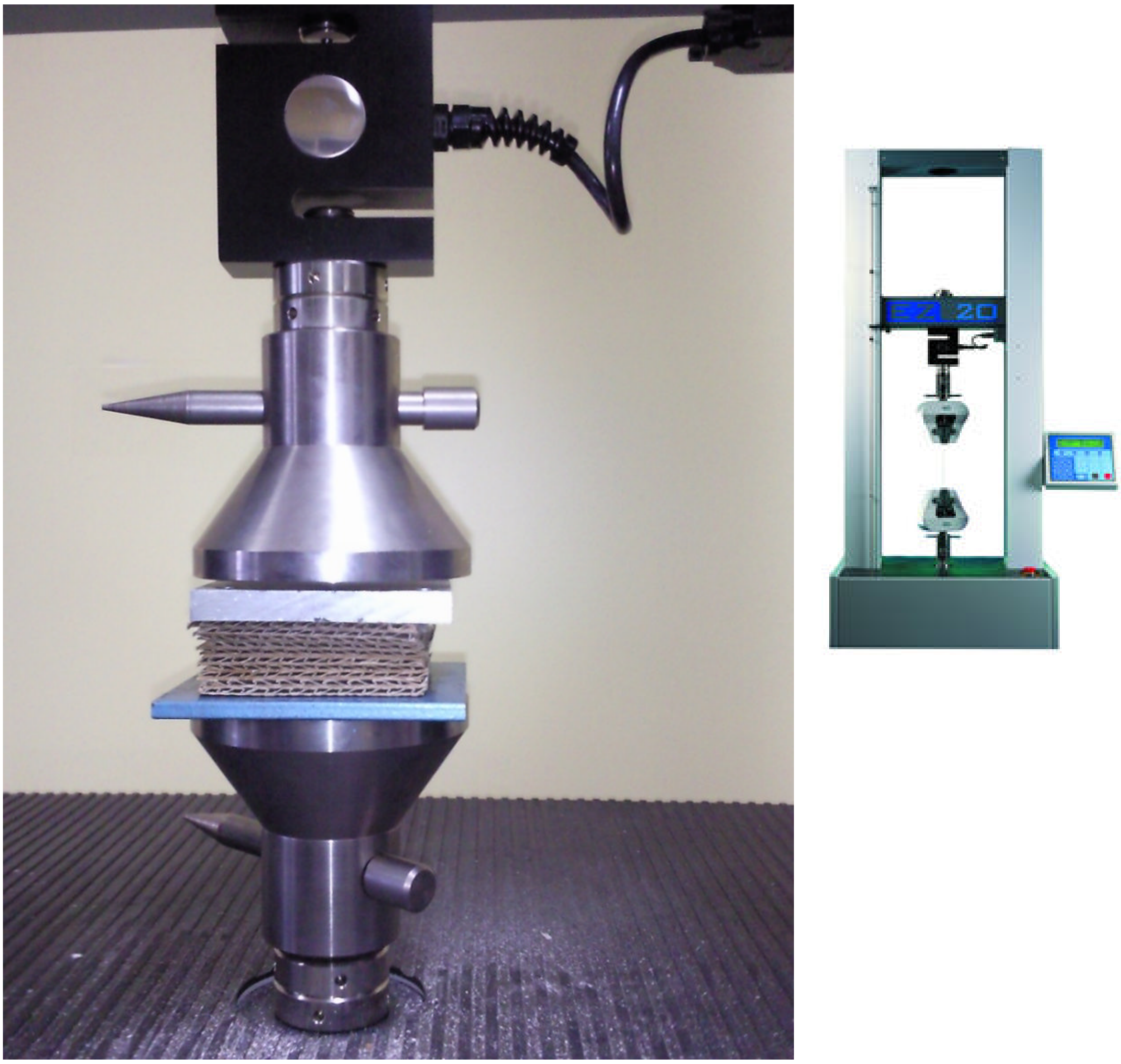


Figure 3.1 Lloyd Universal Tensile Testing Machine Compressing Cushion

A typical result of the pre-compress mechanism for the above samples is shown in figure 3.2. The graph shows that as the load is increased the resistance builds until the first layer collapses then the resistance increases again until the second layer collapses. This continues until all 10 layers have collapsed, creating an oscillating effect on the graph. An explanation on how this occurs is described by Minett and Sek (2000).

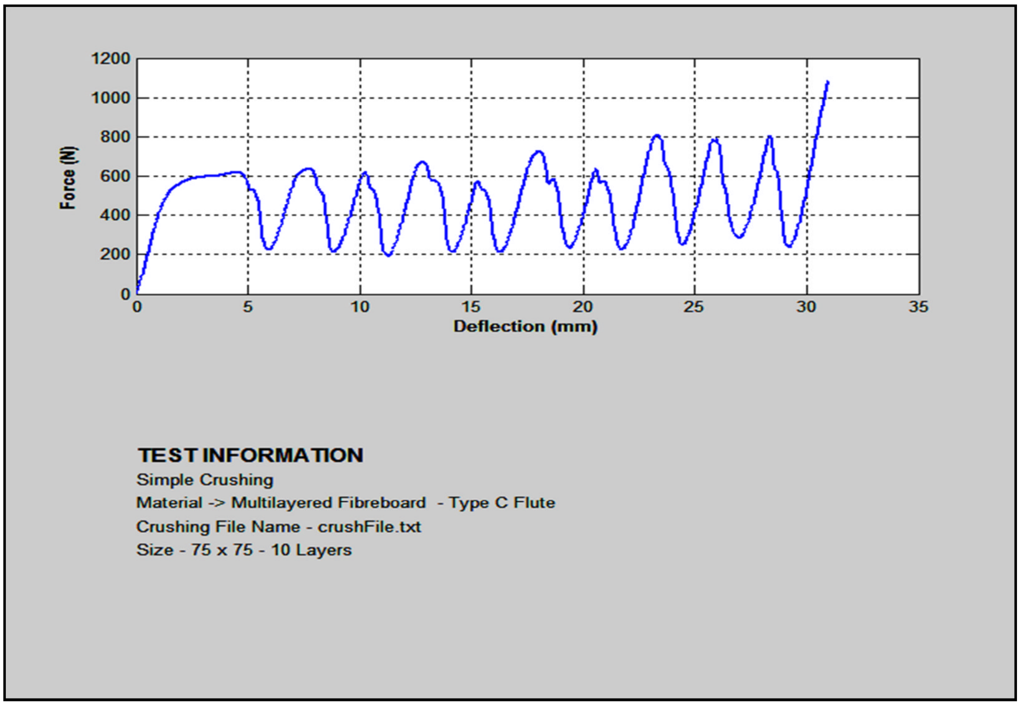


Figure 3.2 Graph of pre-compressing mechanism

After crushing, the cushions are ready for static compression tests to gain an appreciation of the static stiffness and strain which can give some insight into what to expect under creep testing.

3.3. Static Stiffness

The values of static or initial strain can be determined by knowing the material stiffness for the appropriate environmental conditions. This is termed static stiffness. The static stiffness is the slope of an experimental load vs deflection history and can be obtained from the following expressions

$$k = \frac{P}{\Delta\delta}$$

where

k is the stiffness (N/m) (3.2)

P is the applied load (N).

$\Delta\delta$ is the change in deflection for load L (m).

In order to determine the load versus deflection history and subsequently find static stiffness, compression tests were conducted with the load measured for constant increase in deflection (1mm/min) using the Lloyd universal tensile testing machine and the Nexygen data acquisition software, similar to the crushing process described in 3.2. The compression tests were conducted at various humidity levels about an ambient temperature. The samples were required to be cured at the various humidity levels. The curing time was about three hours. This time is not sufficient to fully condition, as was discovered during creep testing. However gives some indication of variations due to the levels of humidity. More detail in the conditioning the cushions for creep testing is discussed later in the chapter.

Preliminary creep testing showed that with a static load of about 1kg mass on the 75mm square samples the creep values amount to about 2-3mm over a period of 160 hours. This would constitute considerable slackness within a package. Therefore an important part of static compression results is the first section between zero and X on the following typical compression test shown in Figure 3.3.

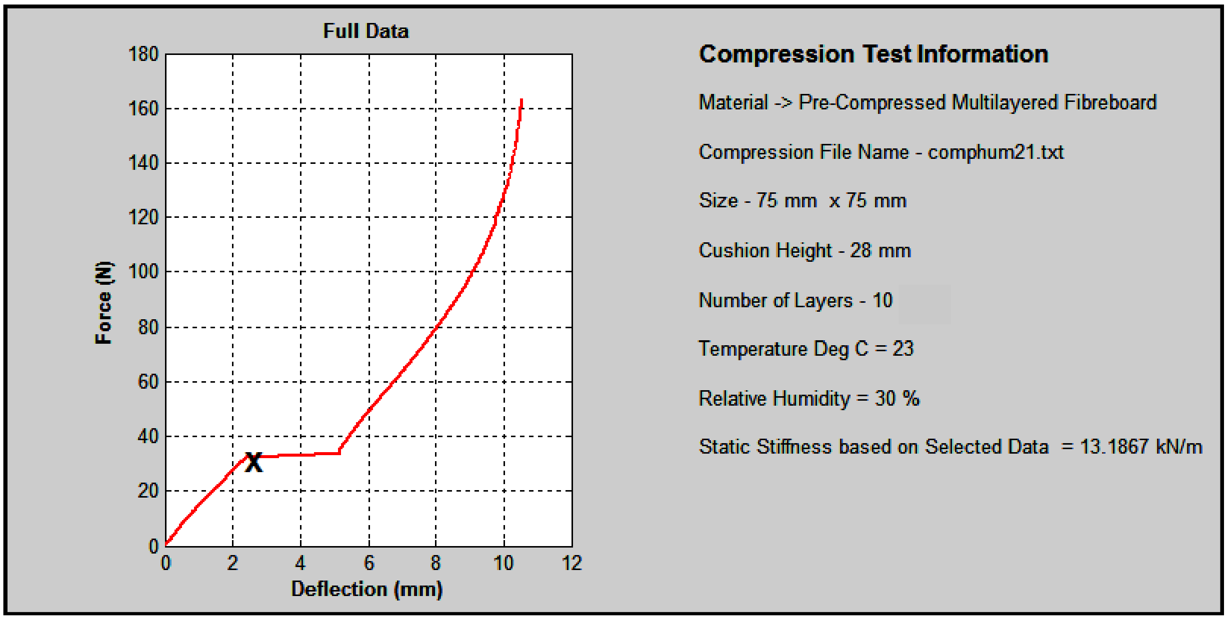


Figure 3.3 Typical Compression Test

3.4. Static Stiffness Results

A typical graphical representation is shown in Figure 3.4. It depicts static compression conducted at 50% relative humidity. The full graphical listing of compression tests at 30, 50, 60, 70 and 80% relative humidity levels are shown in Appendix A. The top graph shows the full static compression result and the lower graph the part from zero to X referred to in Figure 3.3. The test information as well as the resulting static stiffness (zero to X) is displayed. Other stiffness level results are shown in Table 3.1 for the three sample numbers 21, 22 and 23, which are later subjected to creep testing.

Observation of the full data in Figure 3.4 shows an occurrence of the linear and visco-elastic phases after the point X. An attempt was made to simulate this process based on work by Minett, M. W. (2005) who introduced a model that simulated the crushing and visco-elastic phases. This is discussed further in Chapter 4.

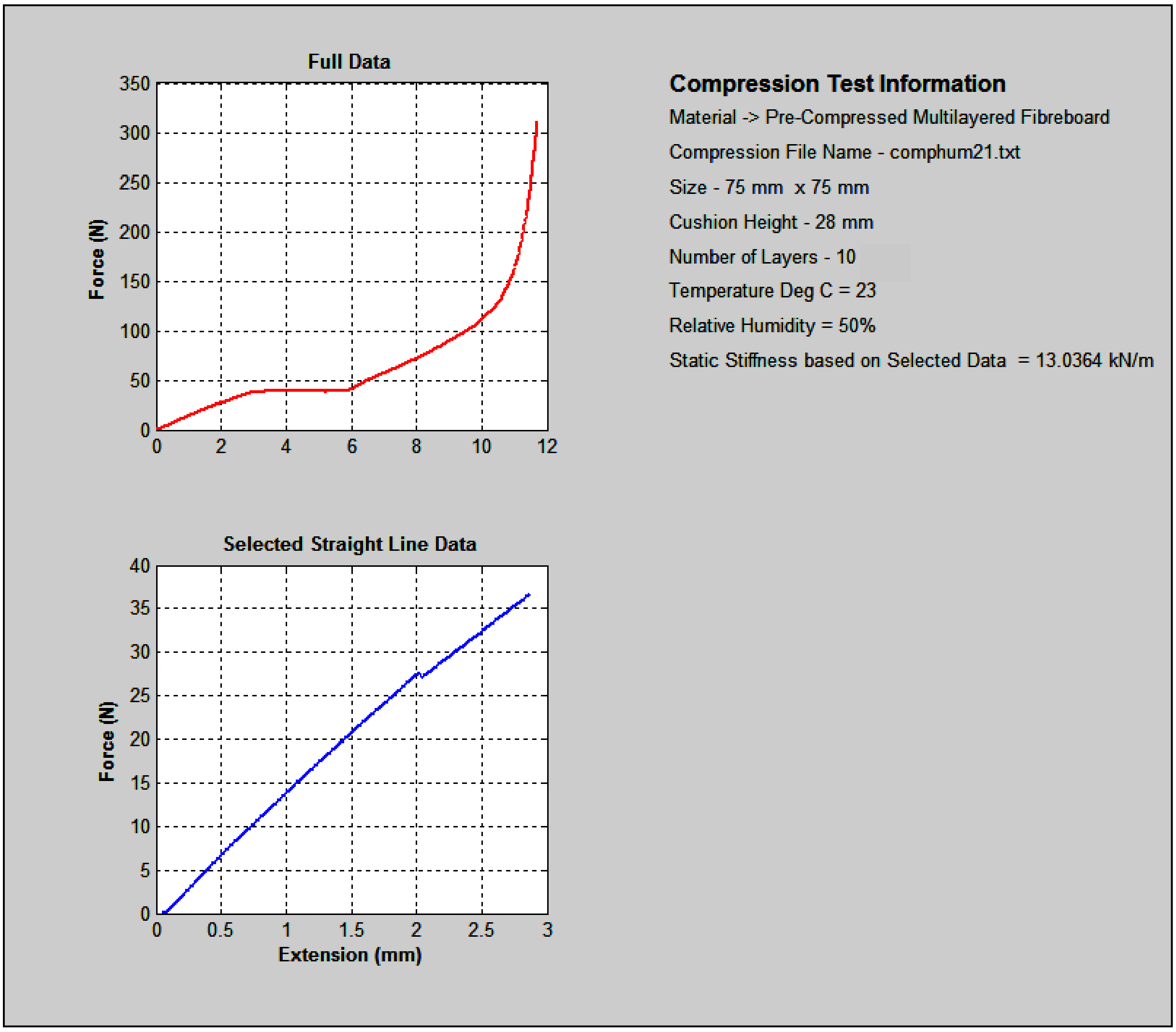


Fig 3.4 Full Compression Data

Table 3-1 Stiffness Results from Static Compression Testing procedure

Static Stiffness Test Results				
Humidity Level	30%		Humidity Level	60%
Sample Number	Static Stiffness kN/m		Sample Number	Static Stiffness kN/m
21	13.385		21	13.576
22	9.669		22	10.093
23	11.74		23	11.906
Humidity Level	50%		Humidity Level	70%
Sample Number	Static Stiffness kN/m		Sample Number	Static Stiffness kN/m
21	13.036		21	12.472
22	10.515		22	9.713
23	12.912		23	11.755

It can be seen from the results in Table 3.1 that the static stiffness has little variation over the humidity range which probably indicates the lack of conditioning. However some knowledge of static stiffness is obtained. Static or initial stiffness can also be experimentally determined from creep by noting the deflection when the load is first applied and then applying to Equation (3.2). Analysis of the static compression is carried out in Chapter 4.

3.5 Creep Strain

The main aim of this study is to ascertain and understand the creep characteristics of multi–layered pre-compressed corrugated fibreboard based on Equation (3.1) or variations.

The static or initial strain mentioned earlier can be determined from the static load and static stiffness obtained experimentally above, using Equation (3.3).

$$\varepsilon_i = \frac{P}{kH} \tag{3.3}$$

where

ε_i is the Static or Initial Strain

k is the static stiffness

P is the applied axial load

H is the original cushion height

Experimental creep strain can be obtained by subjecting the cushions to a steady axial load and measuring deflection at various time intervals over a period of time. Knowing the experimental deflection, the creep strain can be obtained from Equation (3.4).

$$\varepsilon_t = \frac{\delta_t}{H} \tag{3.4}$$

where

ε is the Strain at time t

δ is the deflection at time t

H is the original cushion height

3.6 Pre-Conditioning

As stated in the static compression section, creep data is to be collected for various humidity levels to obtain an appreciation of what occurs in the real environment. Literature tells us that materials such as fibreboard require considerable time to absorb moisture from ambient conditions, particularly as the flutes of multi–layered pre-compressed corrugated fibreboard are quite flat and present a barrier to moisture penetration. Prior to testing, the multi-layer corrugated fibre board cushions need to be conditioned to the requirements of the particular creep test. To be assured that cushions were conditioned to the correct values the following procedure was adopted.

Cushions were first dried in an oven at 200^{o} C for 1.5 hours and the weight noted. After drying, the samples were kept in isolation from the surrounding environment After drying, paper products will absorb moisture from the ambient conditions.

The cushions were placed in an environmental chamber set at appropriate conditions and allowed to absorb moisture. The Relative Humidity levels selected were 30%, 50%, 60%, 70% and 80% at about 23°C. The chamber used is the Computherm 180/190 RHS.

The cushions were weighed at various intervals with mass values recorded until the mass difference was considered small. The reading intervals were firstly on the hour then at larger intervals up to between 96 and 180 hours.

The results in Tables 3.2 to 3.5 show that over the conditioning period the cushions absorb moisture between 4.4 to 10.4 percent, depending on the set humidity level.

Note the absence of 30%, for this value the moisture level came to equilibrium from ambience very quickly and was subsequently exempted from this procedure.

Table 3.2 Conditioning times for 50% RH

Weight of Samples at 50% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	37.13	35.22	34.92
1	37.20	35.26	34.95
2	37.23	35.29	34.97
3	37.25	35.30	34.97
48	37.26	35.30	34.97
72	38.71	36.65	36.36
96	38.75	36.71	36.34
Increased Mass	1.62	1.49	1.42
% Increase	4.36	4.23	4.07

Table 3.3 Conditioning times for 60% RH

Weight of Samples at 60% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	36.80	34.78	34.47
1	37.01	35.00	34.67
2	37.16	35.14	34.81
3	37.27	35.26	34.94
99	37.70	35.65	35.25
147	39.38	37.34	36.98
170	39.25	37.14	36.75
Increased Mass	2.45	2.36	2.28
% Increase	6.66	6.79	6.61

Table 3.4 Conditioning times for 70% RH

Weight of Samples at 70% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	34.94	33.09	32.67
1	35.66	33.80	32.45
2	36.10	34.23	33.88
23	38.01	36.05	35.69
70	38.25	36.18	35.82
119	38.39	36.31	35.91
180	38.56	36.55	36.05
Increased Mass	3.62	3.46	3.38
% Increase	10.36	10.46	10.35

Table 3.5 Conditioning times for 80% RH

Weight of Samples at 80% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	37	38	39
0	36.90	35.06	32.45
1	37.54	35.66	32.98
2	37.81	35.92	33.21
50	38.94	37.11	34.18
98	38.94	37.11	34.17
194	39.54	38.13	34.19
242	40.92	39.12	36.15
Increased Mass	4.02	4.06	3.70
% Increase	10.89	11.58	11.40

3.7 Creep Strain Testing

Immediately after the samples were satisfactorily conditioned to the appropriate RH level creep tests were conducted. A plate was placed on top of the sample and the height recorded after a 0.5kg mass was added. The total load on the sample was 0.840 kg. This resulted in a static stress of 1.464kPa on the 10 layered 7.5cm square samples. This load was deemed satisfactory as it provided a creep result of about 2mm in the preliminary creep test at 30% RH. A creep level of 2mm would be quite unsatisfactory in a package storing delicate instruments, for example, so this seems a reasonable value to employ.

The ASTM Standard D3575 calls for measurements of thickness at time intervals of 6 min, one hour, 24 hours and 168 hours. To gain more data for curve fitting, the following measuring times were adopted. The readings were recorded at intervals, firstly, immediately after placing mass, then at 10 seconds, 6 minutes, 30 minutes. Further measurements were taken at various times until approximately 160 hours, Tables 3.6 to 3.10 show the actual testing times

Deflection values were measured using a digital vernier gauge, with measurements taken five times and averaged, with the following results in Tables 3.6 to 3.10 showing the average readings. The tables also show the corresponding deflections and Creep Strain values based on Equation (3.3). Plots of Creep-Strain versus Time are shown in Figures 3.5 to 3.9.

From the tabular and graphical data it is observed that the Creep Strain does not vary much between the levels of humidity. From the results for the 80% RH level, the strain rate is very swift at the onset which tends to suggest that this material is not satisfactory at this level of humidity. For this reason analysis of this level of humidity is left out of the analysis carried out in Chapter 4.

Table 3.6 Creep Strain Testing Sheet for 30% Humidity Level

Readings and Calculations		Defection Reading (mm)			Creep Values (mm)			Creep Strain Values		
Sample Numbers		21	22	23	21	22	23	21	22	23
	Time (hours)				Static Creep (mm)			Static Strain		
After Placing Plate		29.610	29.180	29.220	0.330	0.160	0.210	0.013	0.007	0.009
After Placing Mass	0.000	29.280	29.020	29.010	0.000	0.000	0.000	0.000	0.000	0.000
	0.517	29.100	28.560	28.610	0.180	0.460	0.400	0.007	0.019	0.017
	1.100	29.260	28.740	28.550	0.020	0.280	0.460	0.001	0.012	0.019
	1.767	28.540	28.360	28.490	0.740	0.660	0.520	0.030	0.027	0.022
	17.810	28.750	27.800	27.700	0.530	1.220	1.310	0.022	0.051	0.055
	19.810	28.400	27.670	27.440	0.880	1.350	1.570	0.036	0.056	0.065
	43.810	27.910	27.020	27.400	1.370	2.000	1.610	0.056	0.083	0.067
	82.560	27.670	26.850	27.150	1.610	2.170	1.860	0.066	0.090	0.077
	118.310	27.270	26.990	26.440	2.010	2.030	2.570	0.083	0.085	0.107
	145.340	27.150	26.830	26.370	2.130	2.190	2.640	0.088	0.091	0.110
	166.310	27.050	26.630	26.340	2.230	2.390	2.670	0.092	0.100	0.111

Table 3.7 Creep Strain Testing Sheet for 50% Humidity Level

Readings and Calculations		Defection Reading (mm)			Creep Values (mm)			Creep Strain Values		
Sample Numbers		21	22	23	21	22	23	21	22	23
	Time (hours)				Static Creep (mm)			Static Strain		
After Placing Plate		28.830	29.960	29.750	0.310	0.240	0.230	0.013	0.010	0.009
After Placing Mass	0.000	28.520	29.720	29.520	0.000	0.000	0.000	0.000	0.000	0.000
	0.067	28.470	29.680	29.468	0.050	0.040	0.052	0.002	0.002	0.002
	1.100	28.410	29.590	29.340	0.110	0.130	0.180	0.005	0.005	0.007
	2.067	28.330	29.380	29.280	0.190	0.340	0.240	0.008	0.014	0.010
	3.067	28.230	29.150	29.240	0.290	0.570	0.280	0.012	0.023	0.011
	4.067	28.160	29.110	29.220	0.360	0.610	0.300	0.015	0.025	0.012
	28.150	27.630	28.620	28.850	0.890	1.100	0.670	0.038	0.044	0.027
	76.150	27.310	28.410	28.570	1.210	1.310	0.950	0.051	0.053	0.039
	101.560	27.250	28.390	28.360	1.270	1.330	1.160	0.054	0.054	0.047
	148.150	27.240	28.320	28.240	1.280	1.400	1.280	0.054	0.057	0.052
	168.150	27.030	28.210	28.270	1.490	1.510	1.250	0.063	0.061	0.051

Table 3.8 Creep Strain Testing Sheet for 60% Humidity Level

Readings and Calculations		Defection Reading (mm)			Creep Values (mm)			Creep Strain Values		
Sample Numbers		21	22	23	21	22	23	21	22	23
	Time (hours)				Static Creep (mm)			Static Strain		
After Placing Plate		29.150	29.650	29.720	0.430	0.430	0.470	0.018	0.017	0.019
After Placing Mass	0.000	28.720	29.220	29.250	0.000	0.000	0.000	0.000	0.000	0.000
	0.017	28.700	29.220	29.230	0.020	0.000	0.020	0.001	0.000	0.001
	0.080	28.680	29.190	29.220	0.040	0.030	0.030	0.002	0.001	0.001
	0.250	28.650	29.160	29.250	0.070	0.060	0.000	0.003	0.002	0.000
	1.250	28.620	29.110	29.250	0.100	0.110	0.000	0.004	0.005	0.000
	2.250	28.310	29.080	29.180	0.410	0.140	0.070	0.017	0.006	0.003
	3.250	28.090	28.750	28.850	0.630	0.470	0.400	0.027	0.019	0.016
	44.250	27.740	27.790	28.120	0.980	1.430	1.130	0.041	0.059	0.047
	85.650	27.650	27.600	27.820	1.070	1.620	1.430	0.045	0.067	0.059
	121.350	27.530	27.440	27.650	1.190	1.780	1.600	0.050	0.073	0.066
	169.250	27.230	27.080	27.340	1.490	2.140	1.910	0.063	0.088	0.079

Table 3.9 Creep Strain Testing Sheet for 70% Humidity Level

Readings and Calculations		Defection Reading (mm)			Creep Values (mm)			Creep Strain Values		
Sample Numbers		21	22	23	21	22	23	21	22	23
	Time (hours)				Static Creep (mm)			Static Strain		
After Placing Plate		28.920	29.640	28.800	0.480	0.650	0.480	0.020	0.026	0.020
After Placing Mass	0.000	28.440	28.990	28.320	0.000	0.000	0.000	0.000	0.000	0.000
	0.167	28.350	28.930	28.310	0.090	0.060	0.010	0.004	0.003	0.000
	0.250	28.290	28.920	28.200	0.150	0.070	0.120	0.006	0.003	0.005
	0.750	28.240	28.730	28.300	0.200	0.260	0.020	0.009	0.011	0.001
	1.667	28.220	28.730	28.240	0.220	0.260	0.080	0.009	0.011	0.003
	2.667	28.140	28.640	28.240	0.300	0.350	0.080	0.013	0.015	0.003
	26.333	27.850	28.120	27.920	0.590	0.870	0.400	0.025	0.036	0.017
	74.333	27.800	27.960	27.780	0.640	1.030	0.540	0.027	0.043	0.023
	110.450	27.770	27.800	27.780	0.670	1.190	0.540	0.029	0.050	0.023
	170.330	27.730	27.650	27.680	0.710	1.340	0.640	0.030	0.056	0.027

Table 3.10 Creep Strain Testing Sheet for 80% Humidity Level

Readings and Calculations		Defection Reading (mm)			Creep Values (mm)			Creep Strain Values		
Sample Numbers		21	22	23	21	22	23	21	22	23
Time (mins)	Time (hours)				Static Creep (mm)			Static Strain		
After Placing Plate		30.960	30.480	29.610	1.150	1.100	1.180	0.044	0.043	0.048
After Placing Mass	0.000	29.810	29.380	28.430	0.000	0.000	0.000	0.000	0.000	0.000
	0.083	29.510	29.360	28.340	0.300	0.020	0.090	0.012	0.001	0.004
	0.167	29.290	28.400	28.330	0.520	0.980	0.100	0.021	0.040	0.004
	0.667	29.780	27.790	28.380	0.030	1.590	0.050	0.001	0.065	0.002
	1.433	29.380	29.030	28.380	0.430	0.350	0.050	0.017	0.014	0.002
	2.750	29.060	28.240	28.270	0.750	1.140	0.160	0.030	0.047	0.007
	26.160	29.060	28.240	28.230	0.750	1.140	0.200	0.030	0.047	0.009
	69.750	29.050	28.220	28.220	0.760	1.160	0.210	0.031	0.048	0.009
	141.833	29.070	28.290	28.320	0.740	1.090	0.110	0.030	0.045	0.005
	189.917	28.740	28.120	28.420	1.070	1.260	0.010	0.043	0.052	0.000

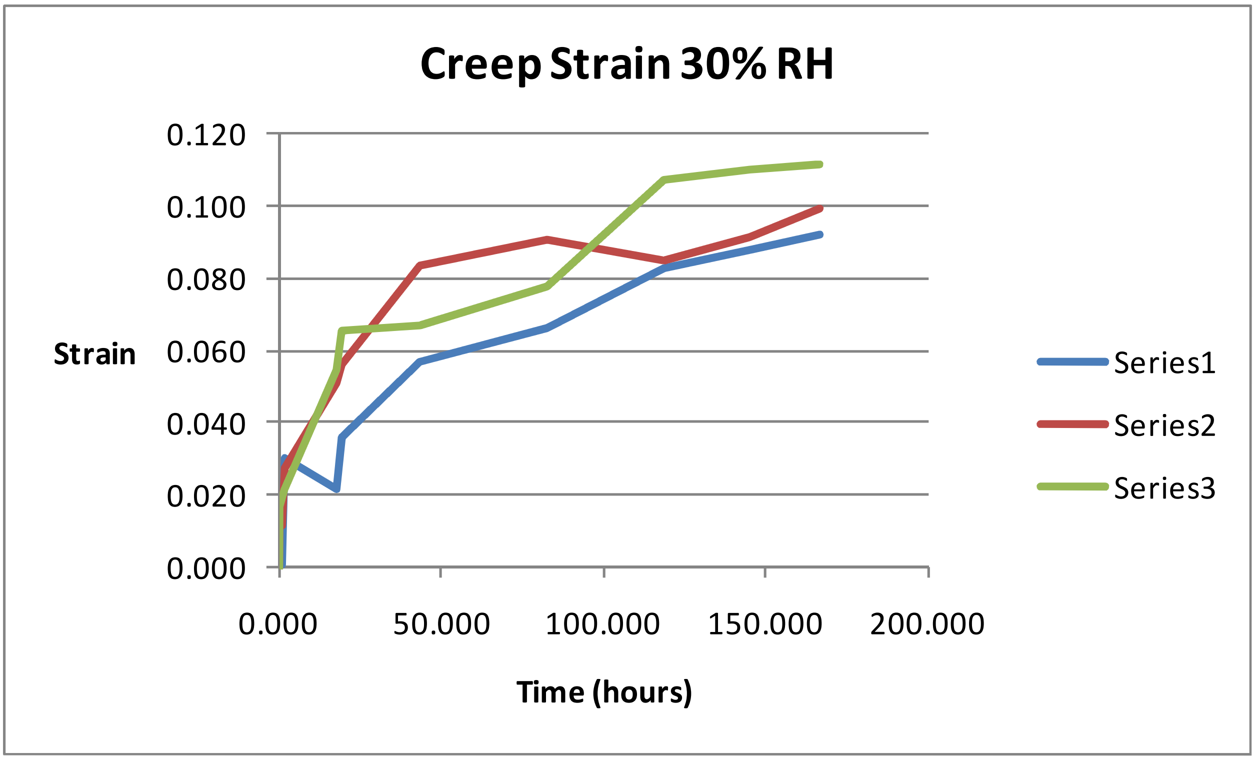


Figure 3.5 Plot of Creep Strain Data at 30% RH (Preliminary Test)

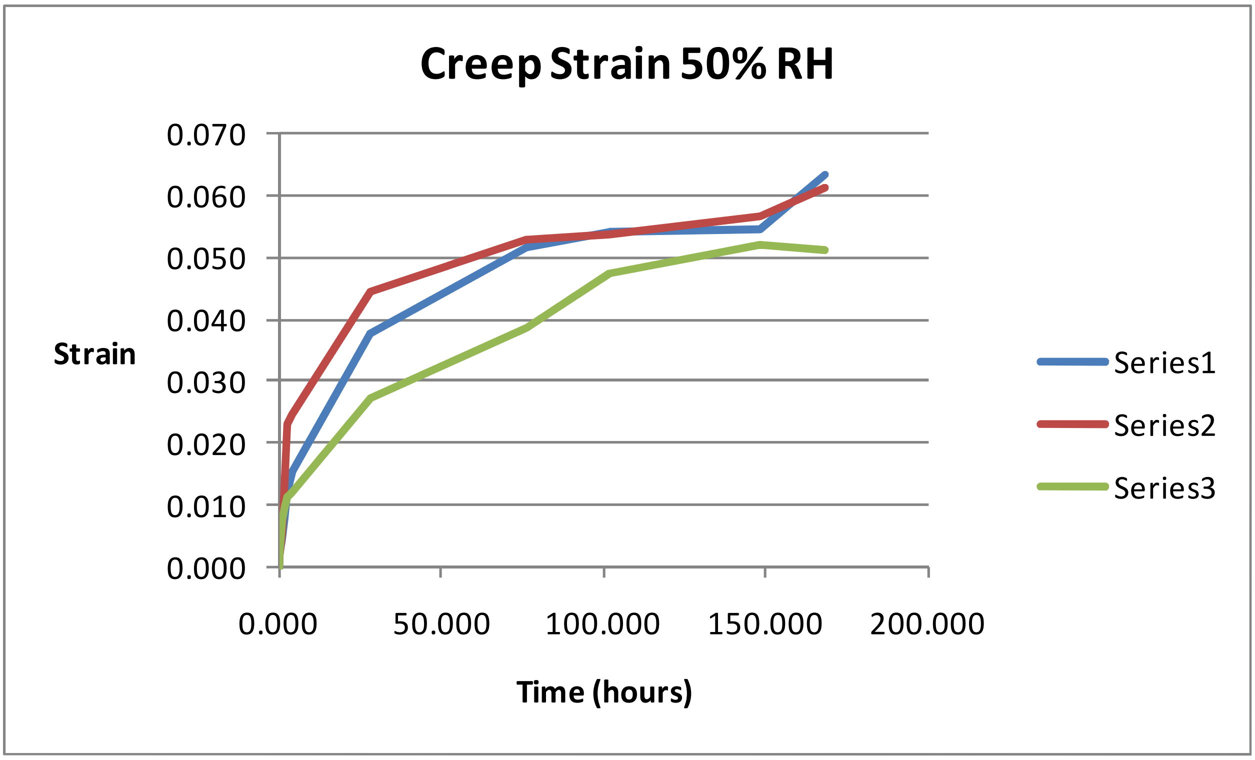


Figure 3.6 Plot of Creep Strain Data at 50% RH

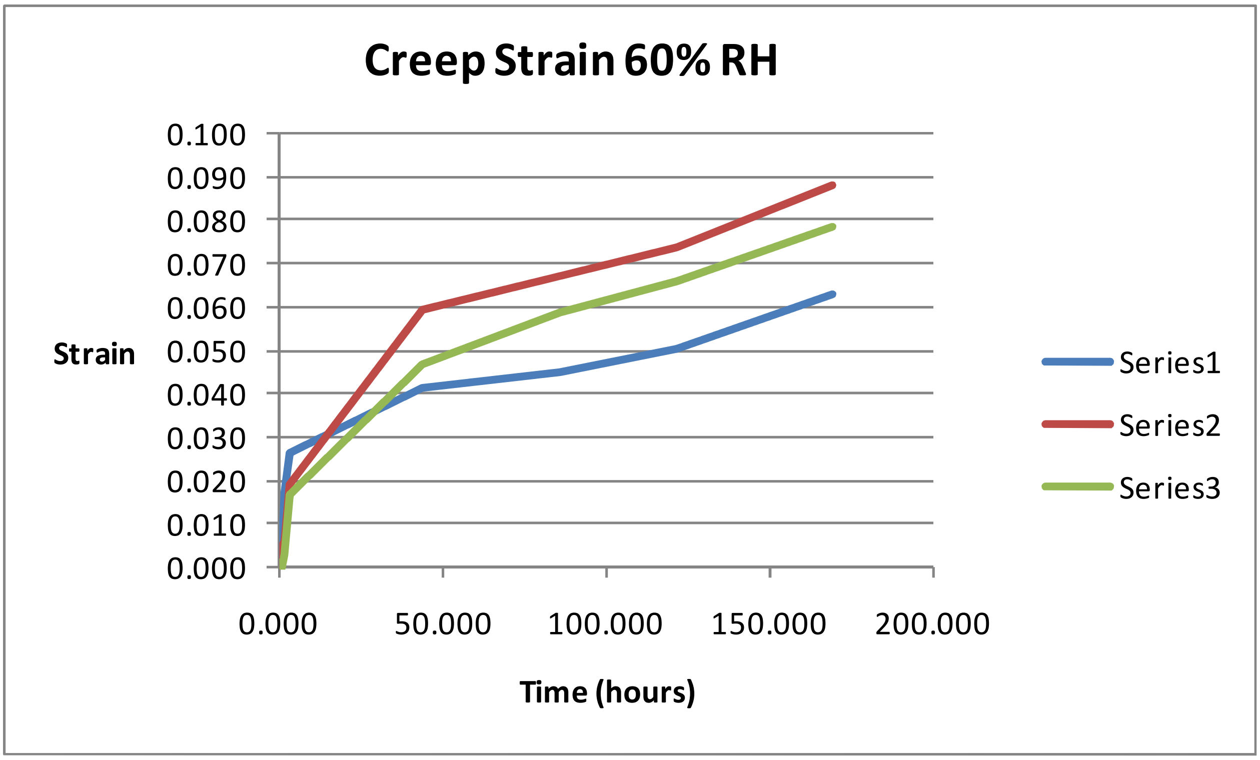


Fig 3.7 Plot of Creep Strain Data at 60% RH

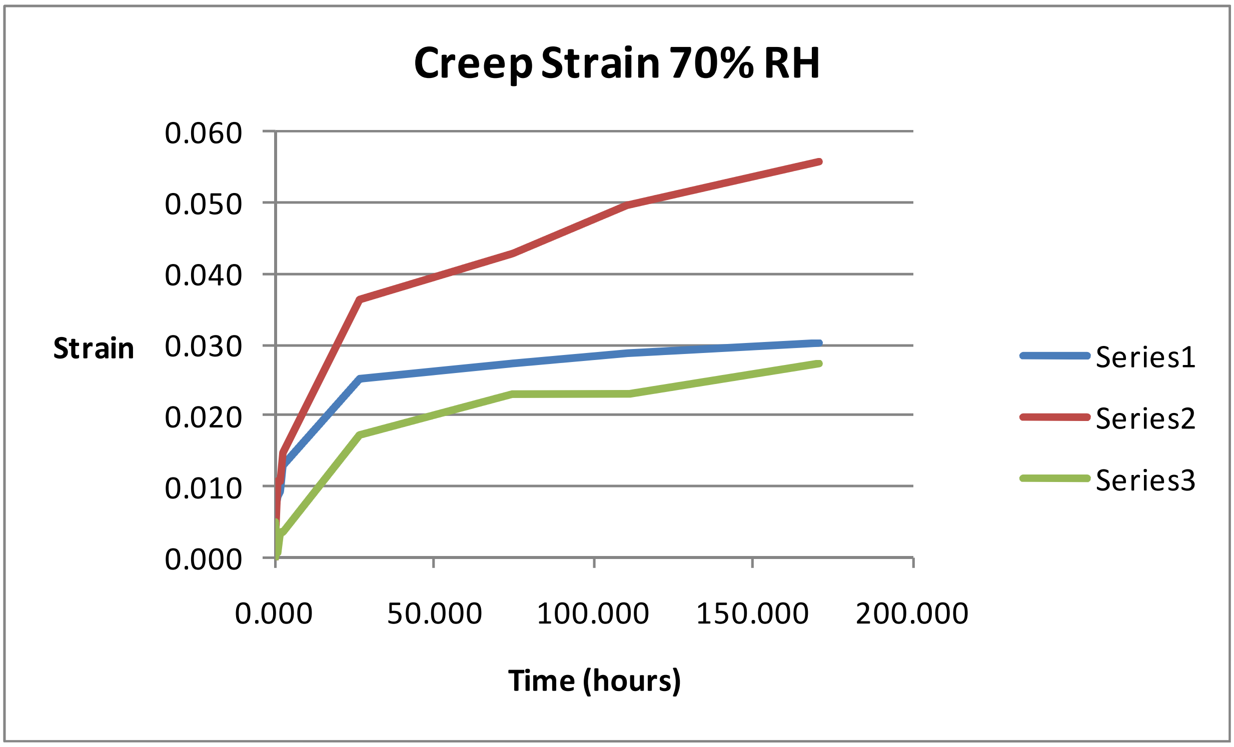


Fig 3.8 Plot of Creep Strain Data at 70% RH

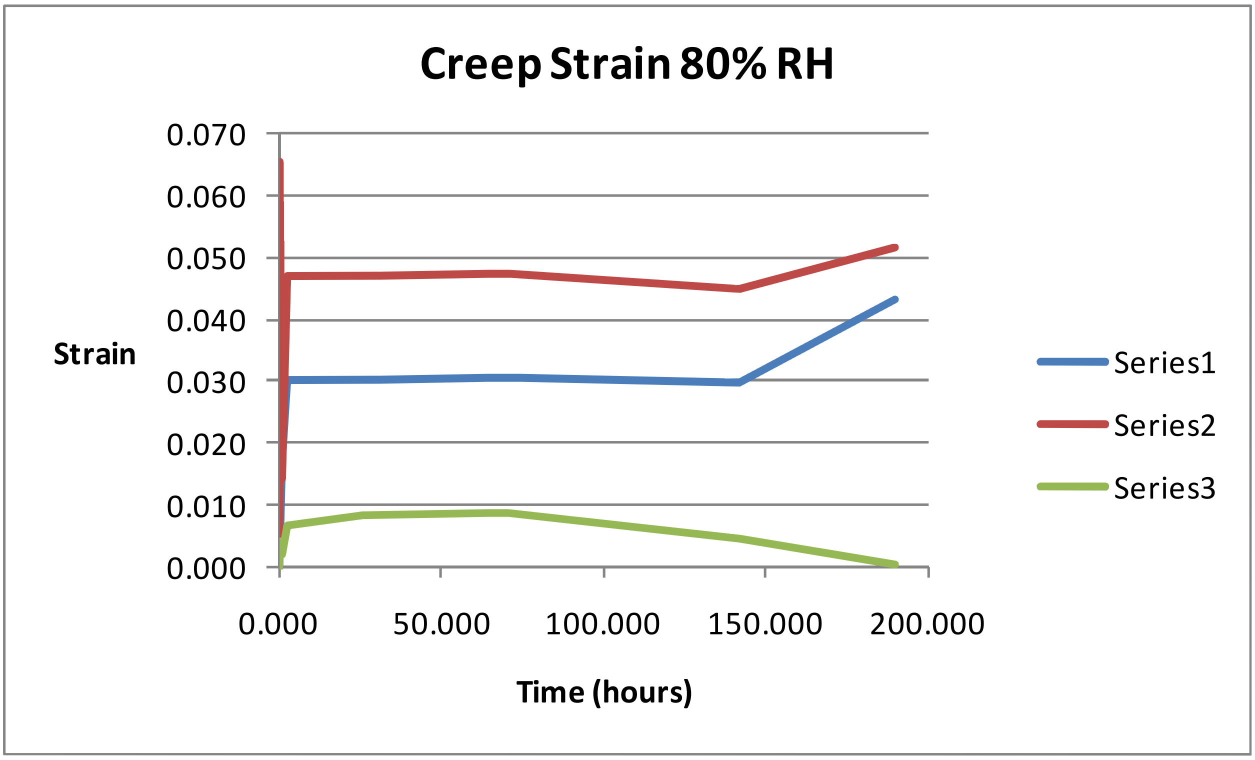


Fig 3.9 Plot of Creep Strain Data at 80% RH

Chapter 4 Model Development and Analysis

4.1. Introduction to Analysis

Although the main focus for this study is the creep characteristics of pre-compressed multi-layered corrugated fibreboard, it was necessary to perform crushing and experimental static compression work. It is also worthwhile analyzing the static compression data.

4.2. Crushing of Material Analysis

From the experimental work in Chapter 3, typical results of crushing of multi–layered pre-compressed corrugated fibreboard are shown in Figure 4.1.

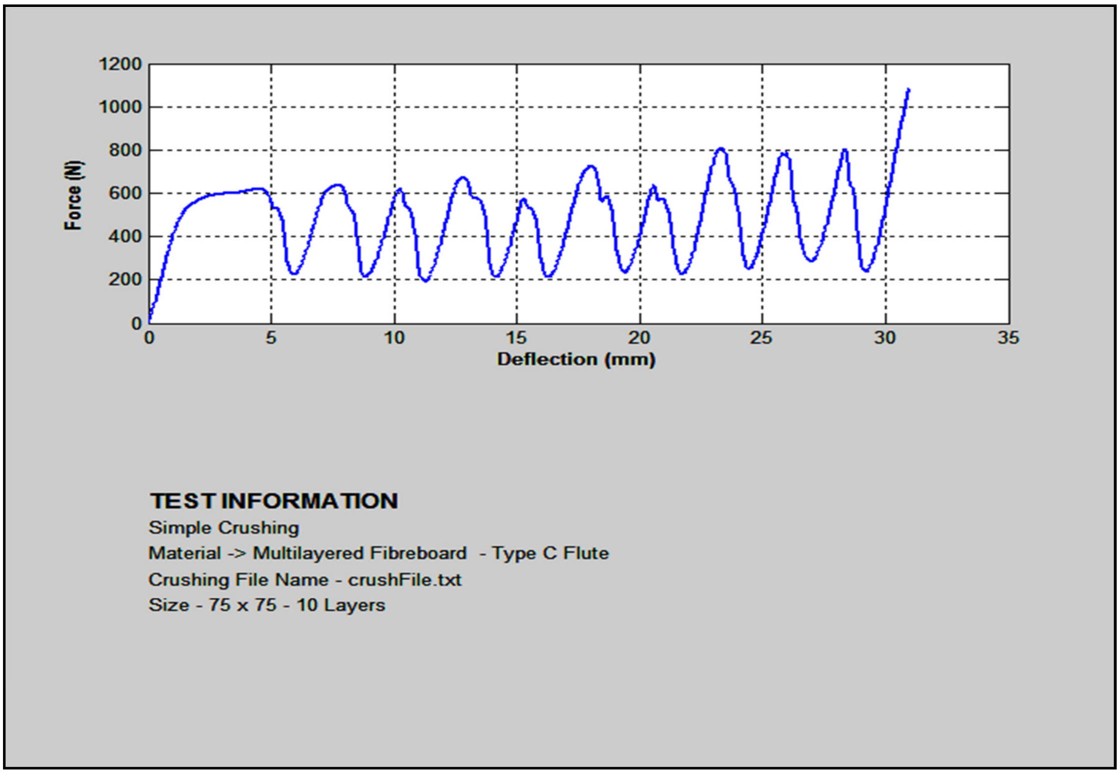


Figure 4.1 Typical Cushion Crushing Results

The model Minett, M. W. (2005) introduced to simulate the elastic, visco-elastic and crushing phases of pre-compressing multi-layered corrugated fibreboard is used here. The model is presented as Equation(4.1).

$$
\begin{aligned}
&P1 = F_m\left(1 - e^{-a\varepsilon}\right) \qquad \text{Phase 1 Semi-Elastic}\\
&P2 = SF\left(\frac{1}{\left(\varepsilon_0 - \varepsilon\right)} - \frac{1}{\varepsilon_0}\right) \quad \text{Phase 2 Visco-Elastic}\\
&P3 = F_a \cos\left(2N\pi y / b\right) \quad \text{Periodic Phase}\\
&F = P1 + P2 + P3\\
&\text{Therefore}\\
&F = F_m\left(1 - e^{-a\varepsilon}\right) + SF\left(\frac{1}{\left(\varepsilon_0 - \varepsilon\right)} - \frac{1}{\varepsilon_0}\right) + F_a \cos\left(2N\pi y / b\right)\\
&\text{where}\\
&F = \text{ the instantaneous force}\\
&F_m = \text{ the mean force}\\
&F_a = \text{the alternating force}\\
&SF = \text{ the slope factor}\\
&N = \text{ the number of cushion layers}\\
&y = \text{ the displacement record}\\
&\varepsilon = \text{ the strain - the ratio of deflection to unloaded thickness}\\
&\varepsilon_0 = \text{ the maximum strain}\\
&\text{b is a multiplier}
\end{aligned}
\tag{4.1}
$$

Using of the samples from the experimental work of Chapter 3, a simulation was conducted and shown in Figure 4.2.

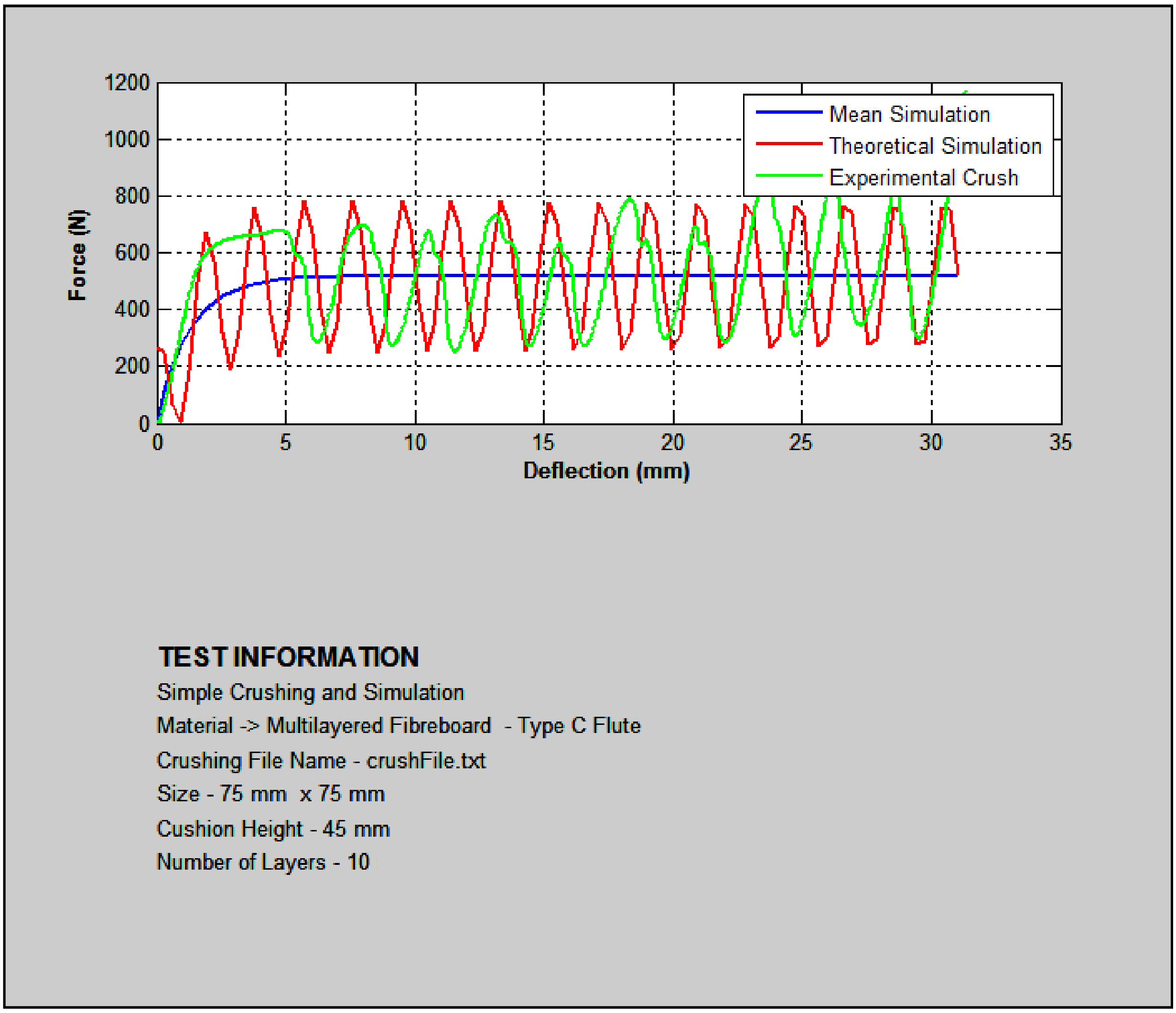


Figure 4.2 Pre-Compressing Mechanisms – Experimental and by Modeling

4.3. Static Compression of Pre-Compressed State Analysis

It is important to determine if the compression test results on pre-compressed multi-layered corrugated fibreboard cushion can be modeled. Is it possible to use the non-periodic parts of the model, i.e. P1 and P2, to represent static strain of pre-compressed corrugated fibreboard cushions?

The model is repeated as Equation (4.2), less the periodic section of Equation (4.1) to reflect pre-compressed state and is referred to as Compression Model 1.

Taking a typical graph of Force versus Deflection from the compressive deflection testing shown in figure 4.3, at 50% RH and applying the model, it is possible to predict the Compressive Strain of Multilayered Pre-Compressed Corrugated Fibreboard cushions.

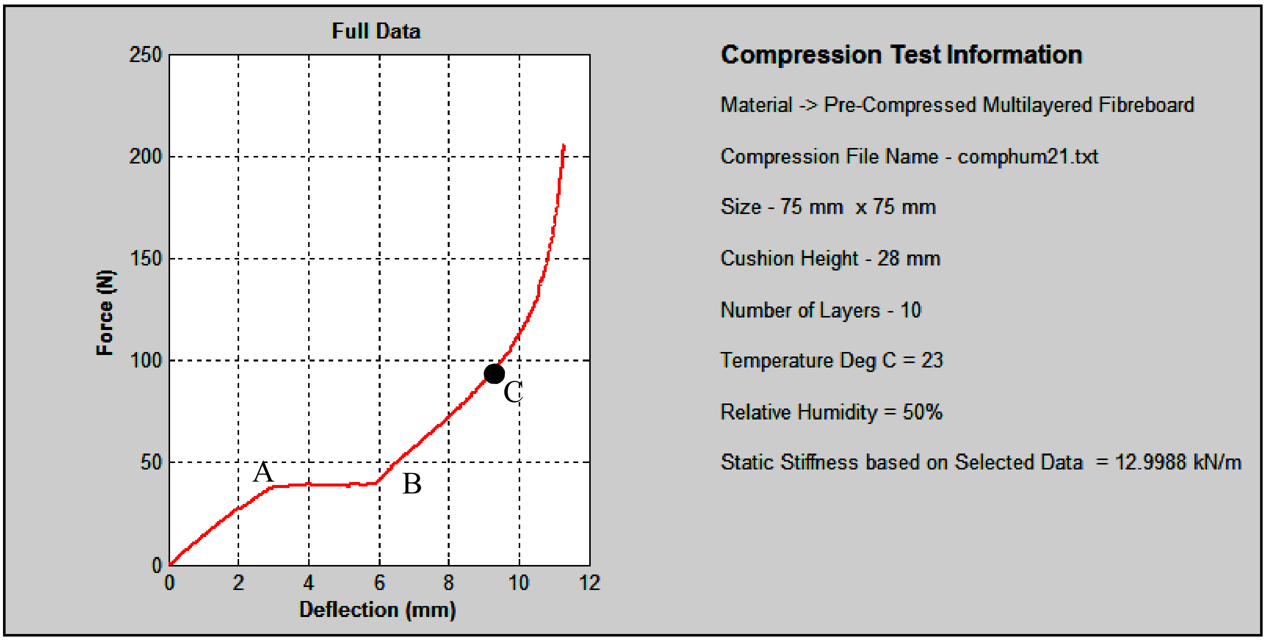


Figure 4.3 Typical Static Strain Test

Compression Model 1

$P1 = F_m\left(1 - e^{-a\varepsilon}\right)$ Phase 1 Semi-Elastic

$P2 = SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right)$ Phase 2 Visco-Elastic

$F = P1 + P2$

Therefore

$$F = F_m\left(1 - e^{-a\varepsilon}\right) + SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right) \qquad (4.2)$$

It may also be prudent to develop models making use of the Compressive Stiffness data (Compression Model 2) that can be determined from the static testing.

Compression Model 2

Phase 1 and 2 Elastic

$P_1 = \delta * SS1$ for $\delta = 0 \rightarrow \delta_A$ and

$P_1 = Force(\delta_A)$ for $\delta = 0 \rightarrow \delta_C$ and

$P_2 = \delta * SS2$ for $\delta = \delta_B \rightarrow \delta_C$ and

Phase 3 Visco-Elastic

$P3 = SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right)$

Therefore the simulated force is

$F = P1 + P2 + P3$

δ is the experimental deflection

SS1 and SS2 are the Static Strains

F is the Simulated Force corresponding to

Compressive Strain (4.3)

To compare the static compression experimental data with models 1 and 2, software has been written using Matlab® revision R2007b. The software produces the results of these simulations in terms of Force vs Strain and are compared with experimental results. Typical results are shown in Figure 4.4 to 4.7 inclusively, with a full display contained in Appendix A.

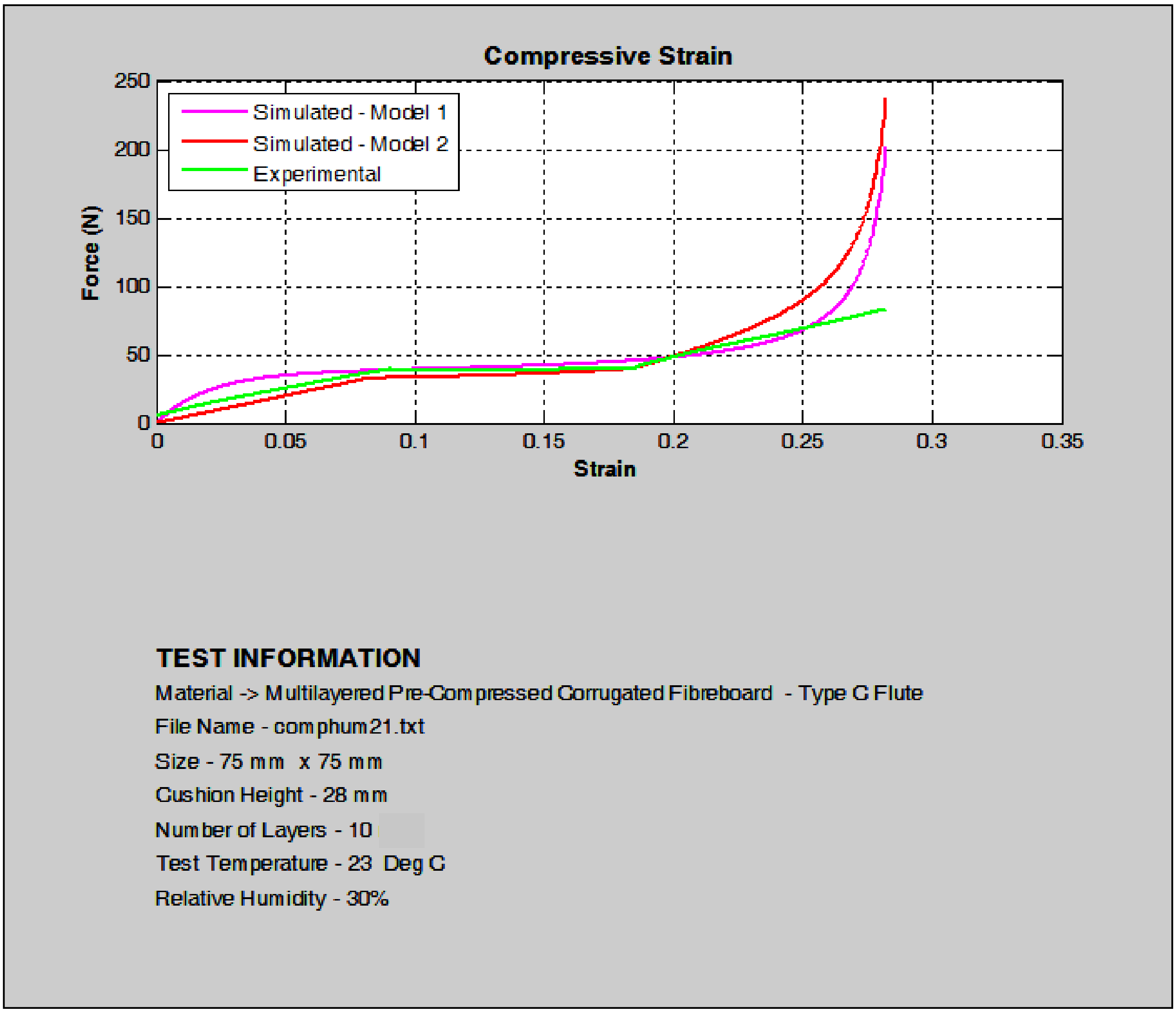


Figure 4.4 Compression and Simulation at 30% Humidity based on Equations 4.2 and 4.3

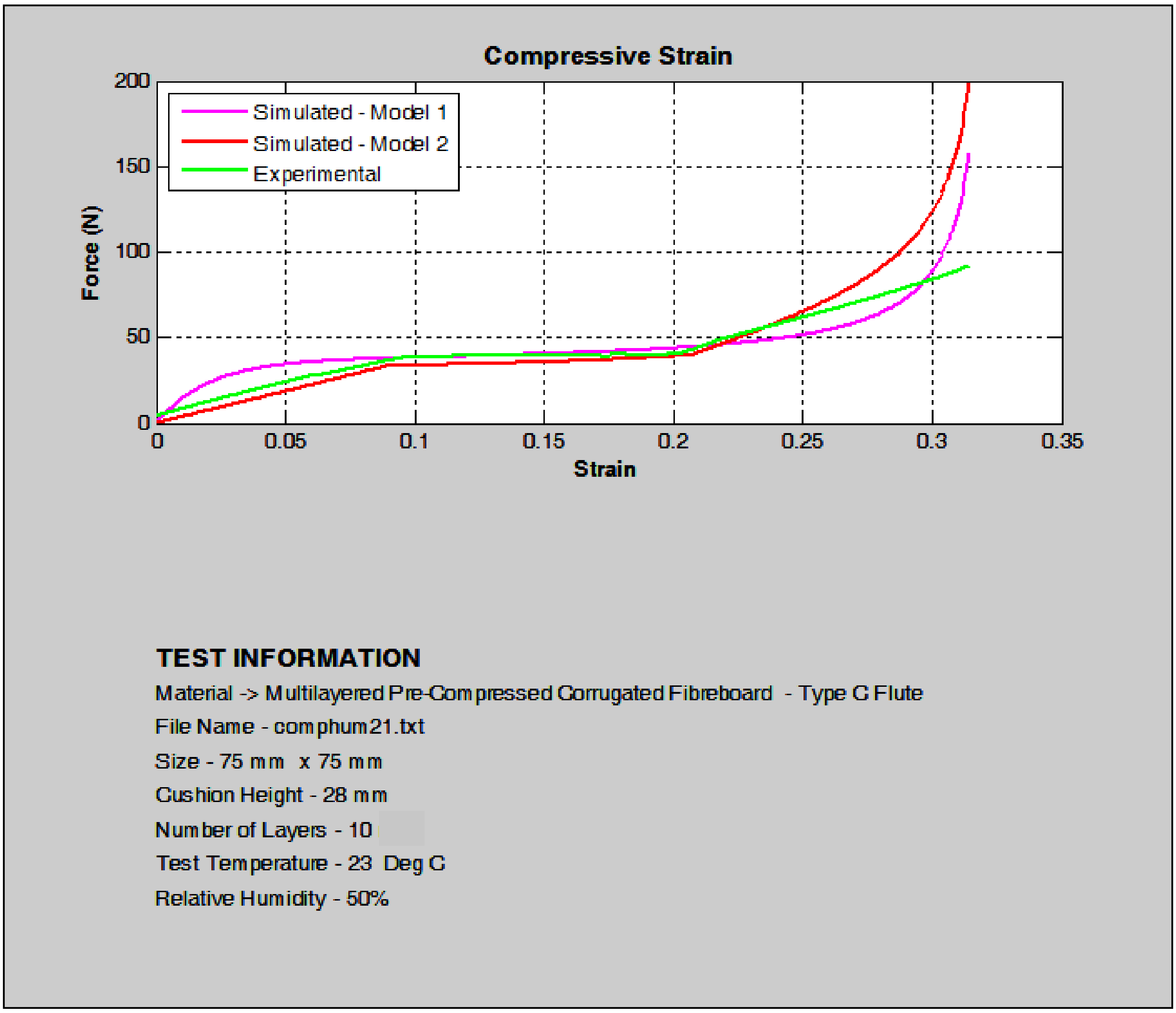


Figure 4.5 Compression and Simulation at 50% Humidity based on Equations 4.2 and 4.3

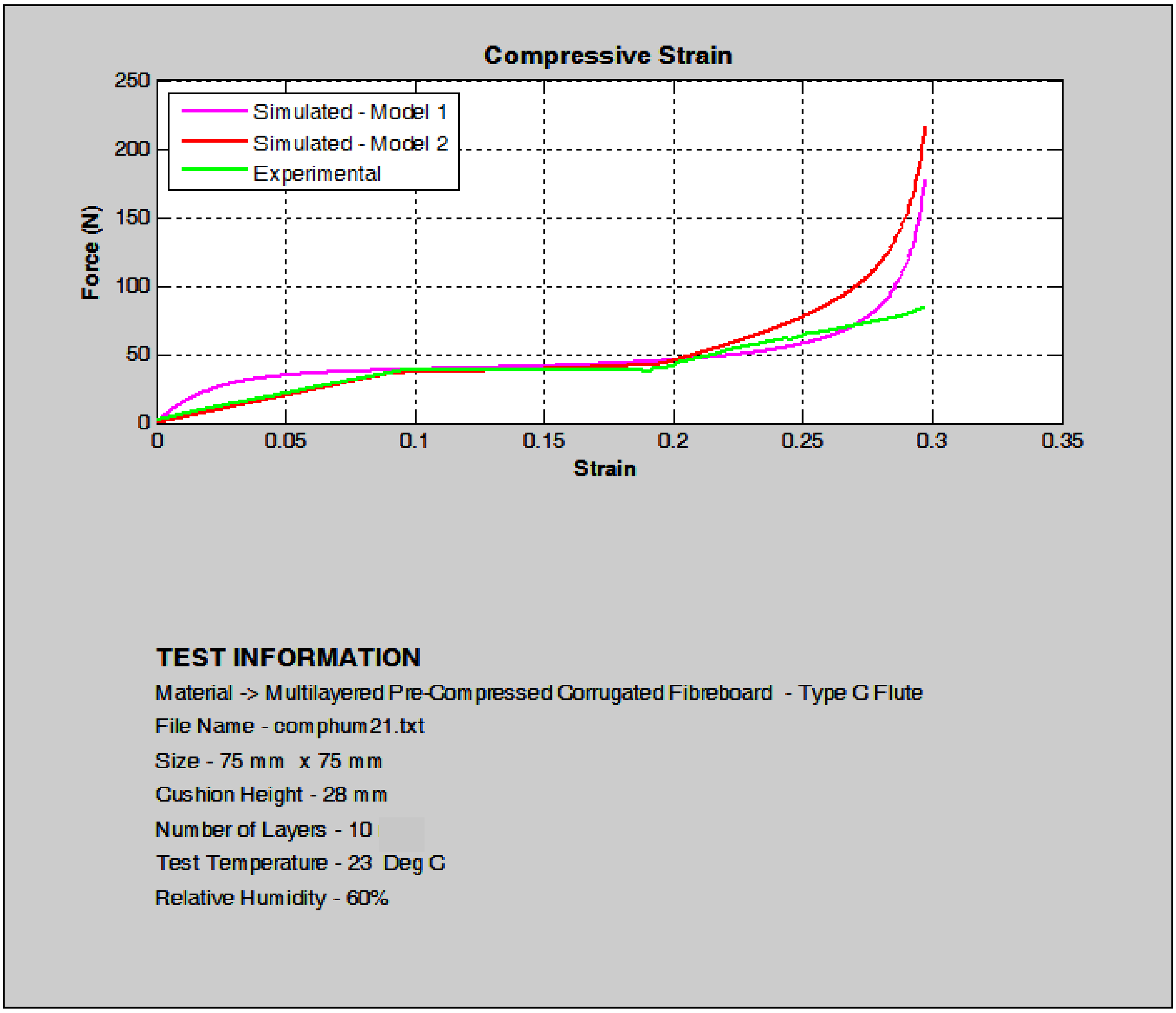


Figure 4.6 Compression and Simulation at 60% Humidity based on Equations 4.2 and 4.3

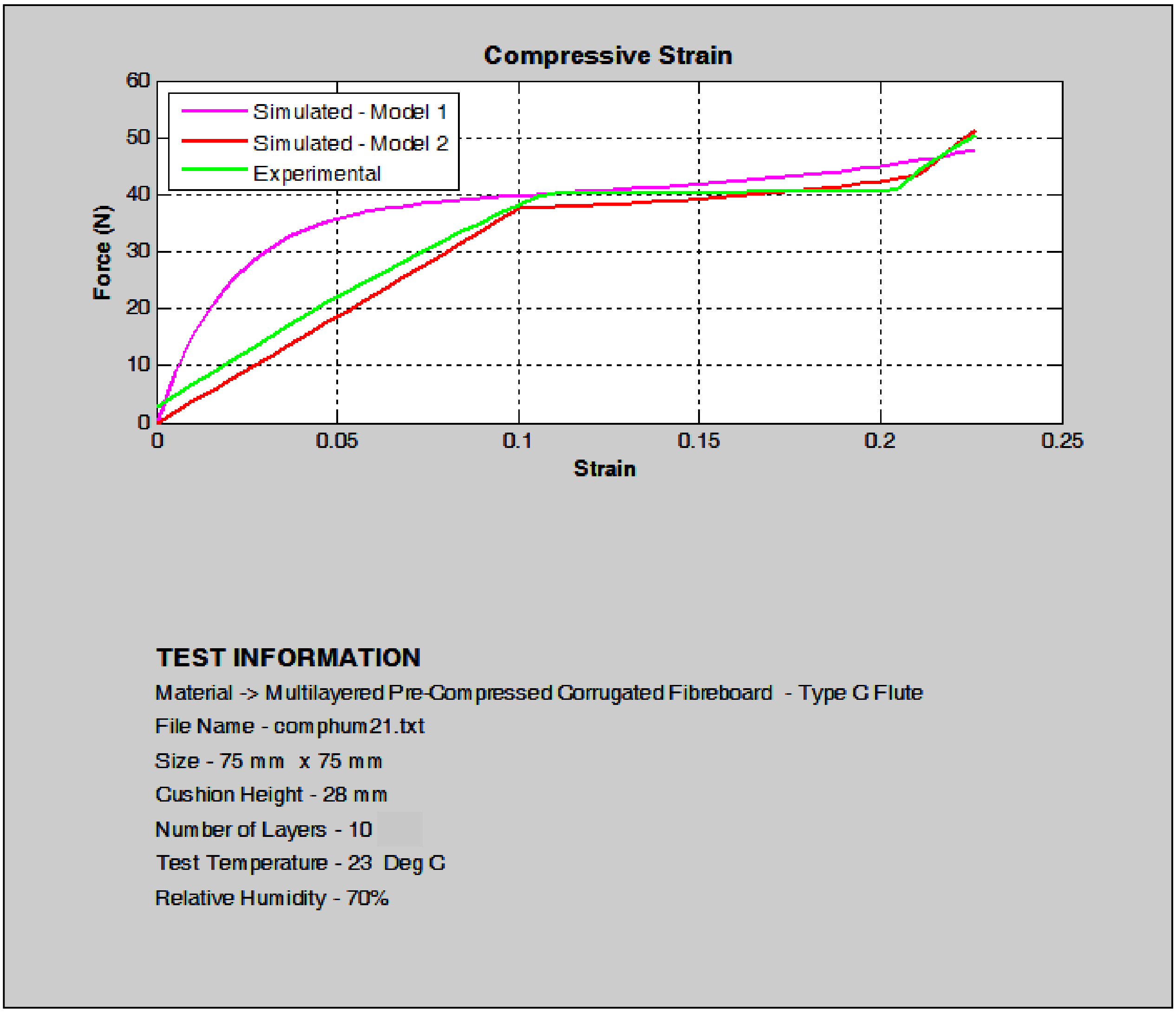


Figure 4.7 Compression and Simulation at 70% Humidity based on Equations 4.2 and 4.3

4.4. Creep Strain Analysis

Analysis on the creep data obtained experimentally and described in Chapter 3 can be carried using optimized curve fitting on the Voigt model of Viscoelasticity, referenced in Chapter 2. The model is repeated here as Figure 4.8 and Equation (4.4).

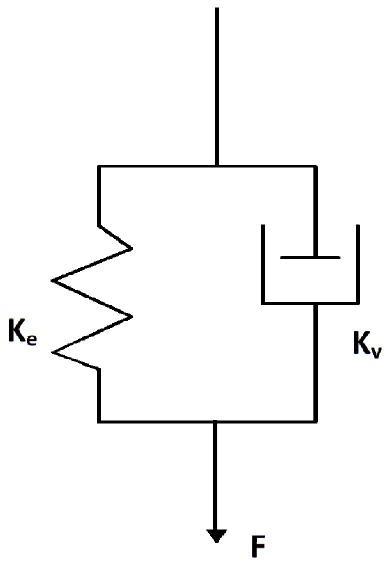


Figure 4.8 Voigt Model of Viscoelasticity

$$\varepsilon_t = \varepsilon_\infty\left[1 - \exp(-t/\tau)\right] \tag{4.4}$$

where

ε_t is the strain at time t

ε_∞ is the final strain

τ is the relaxation time

For a creep test on pre-compressed corrugated fibreboard cushions the value of final strain is essentially unknown as the Voigt model is exponentially decaying. The final strain could be replaced with the static strain, which is experimentally known, multiplied by a factor. So for the purpose of applying Equation (4.4) to experimental data the following substitutions will apply.

$$\varepsilon_t = a\,\varepsilon_i\left[1-\exp\left(-t/\tau\right)\right] \tag{4.5}$$

where a is an experimental multiplier of the static Strain ε_i and τ is the relaxation time

A more general expression using the static stress and stiffness together with experimental multipliers shown in Equation (4.6) may be more pertinent than Equation (4.5). It was also determined by some preliminary simulation that both equations give similar results.

$$\varepsilon_t = a\frac{\sigma_i}{k_i}\left[1-\exp\left(-\beta t\right)\right] \tag{4.6}$$

where a and β are experimental multipliers

σ_i is the Static Stress

k_i is the Static Stiffness

It should be noted by inspection of Equations (4.5) and (4.6), that as the exponents tend towards 1 the value within the square brackets becomes 0.63 that is 63% of the total strain. As the value of the exponent becomes smaller, which occurs as time increases, and then the value in the square bracket reduces to one and leads to the value of creep strain described in Equation (4.7)

$$\varepsilon_t = a\,\varepsilon_i \quad \text{or} \quad \varepsilon_t = a\frac{\sigma_i}{k_i}$$

where a is an experimental multiplier (4.7)

ε_i is the static strain

σ_i is the Static Stress

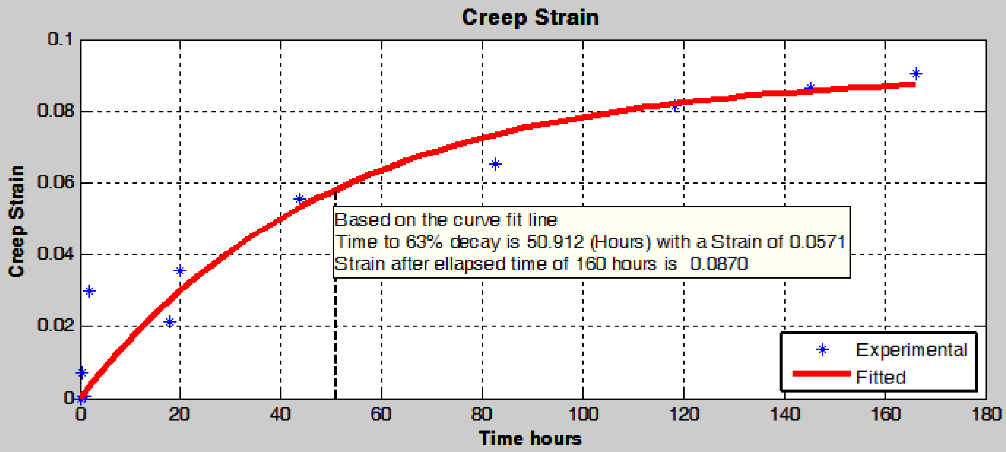
k_i is the Static Stiffness

To analyse the experimental data a non-linear technique is used to fit the experimental data to expressions (4.5) and (4.6). Software has been written using Matlab® revision R2007b, which has a non-linear equation solver function based on the Least Squares algorithm. The Matlab function is based on finding the coefficients x, by optimizing the following Least Squares expression:

$$\frac{1}{2}\sum_{i=1}^{m}\left(f\left(x, xdata_i\right) - ydata_i\right)^2$$

It returns optimized values of x and information about the Least Squares fit as the residuals are minimized.

The following graphs are the curve fitting results for cushion sample 21 at 30% RH through to 80% RH using both functions (4.5) and (4.6). Simulations for all samples can be found in Appendix B. The results of these simulations are presented in Tables 4.1 and 4.2



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 14.863 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0134

Static Stress σ_i = 1.482 kPa

Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1\text{-}e^{-t/\tau})$

Fitted Constants -> a = 6.738 τ = 49.404

Figure 4.9 Creep Experimental and Simulation sample 21 at 30% RH using Equation 4.5

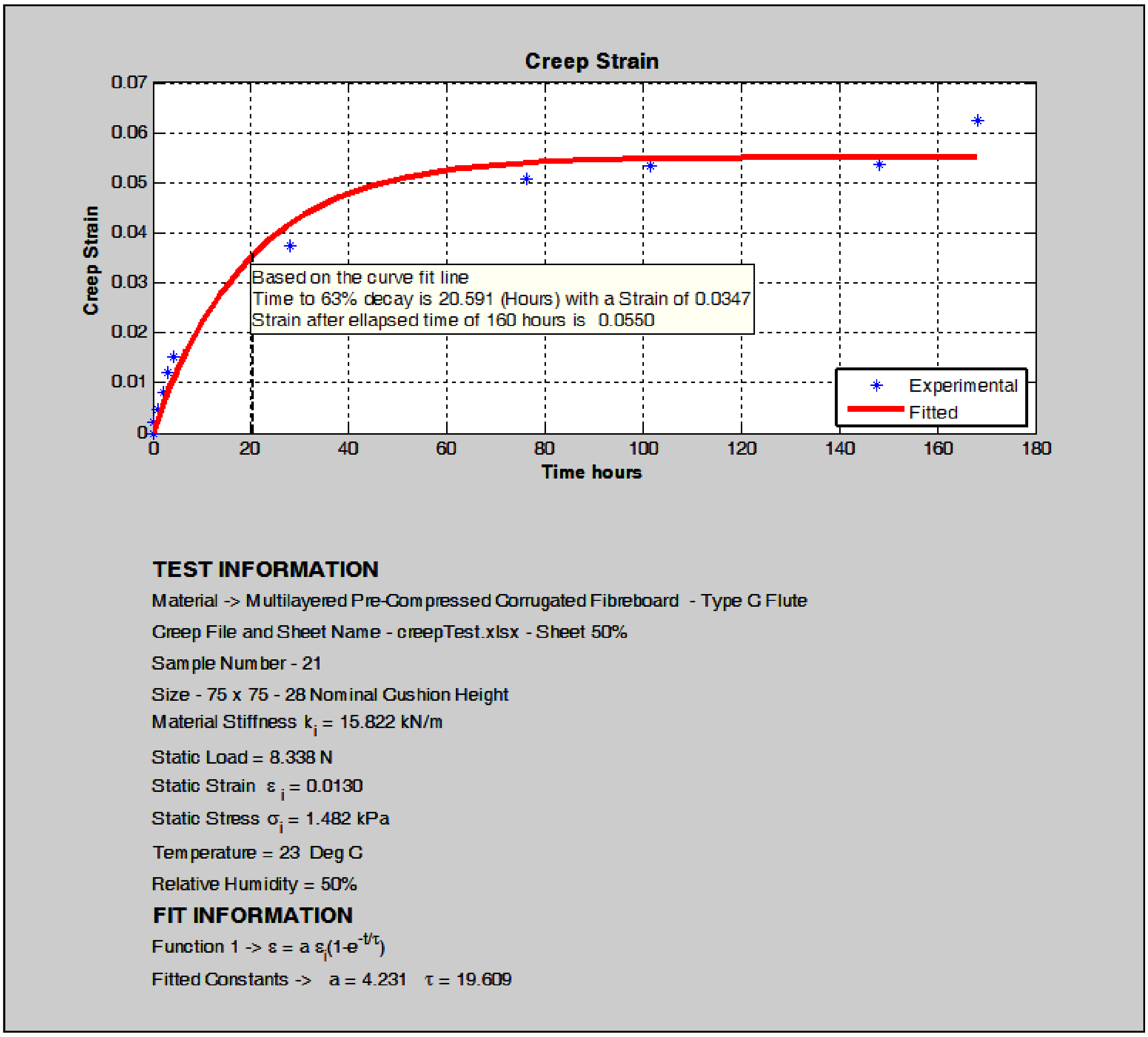


Figure 4.10 Creep Experimental and Simulation sample 21 at 50% RH using Equation 4.5

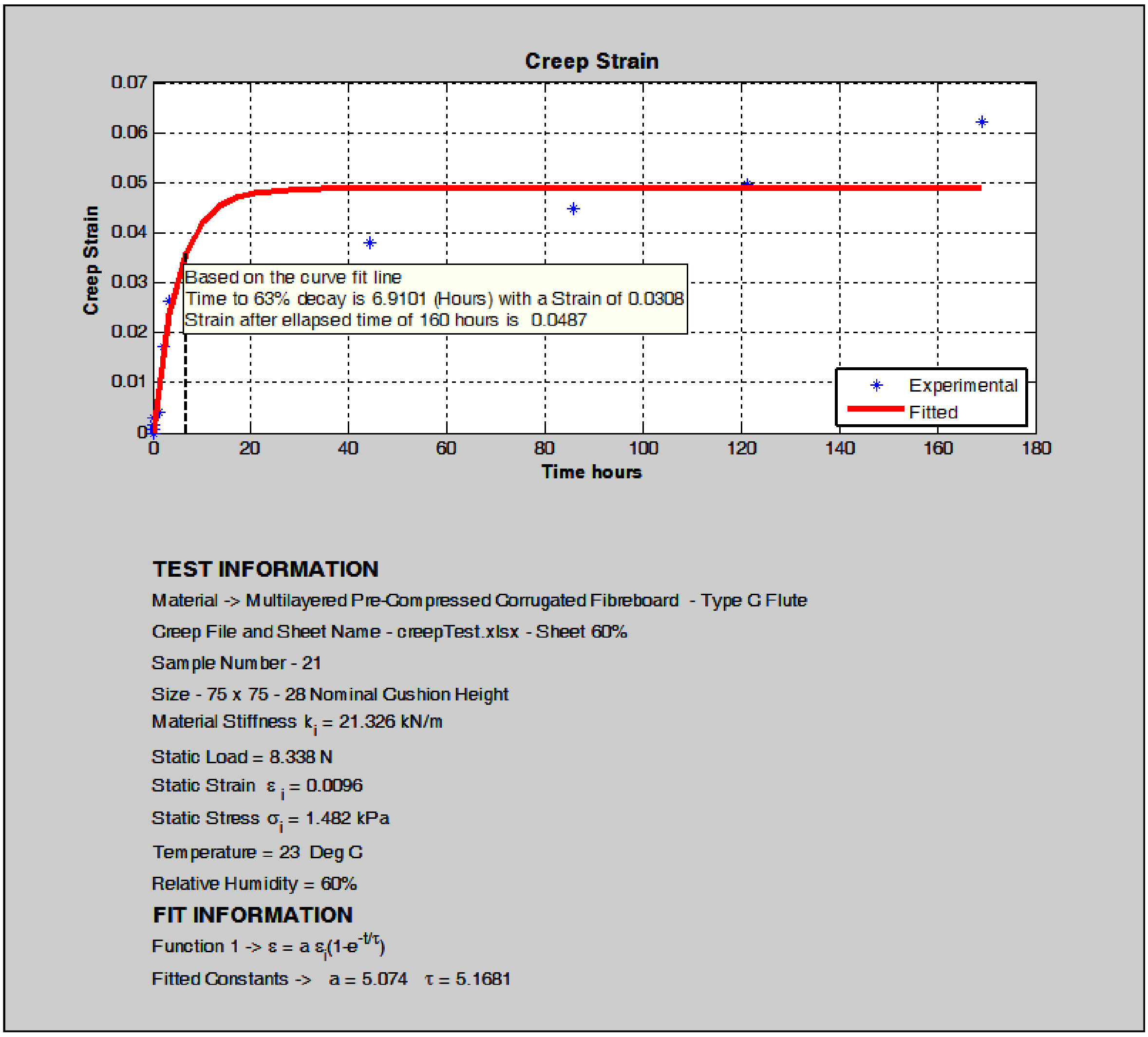
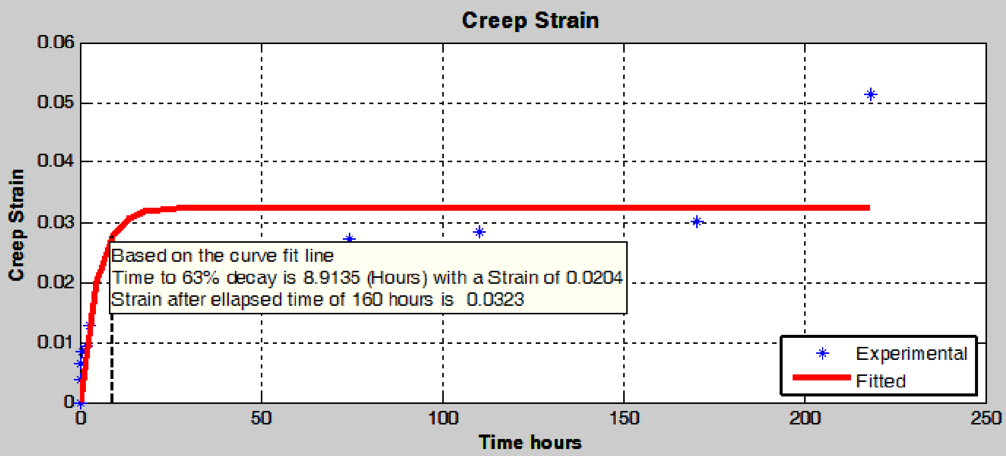


Figure 4.11 Creep Experimental and Simulation sample 21 at 60% RH using Equation 4.5



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 27.250 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0076

Static Stress σ_i = 1.482 kPa

Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1\text{-}e^{-t/\tau})$

Fitted Constants -> a = 4.246 τ = 4.5535

Figure 4.12 Creep Experimental and Simulation sample 21 at 70% RH using Equation 4.5

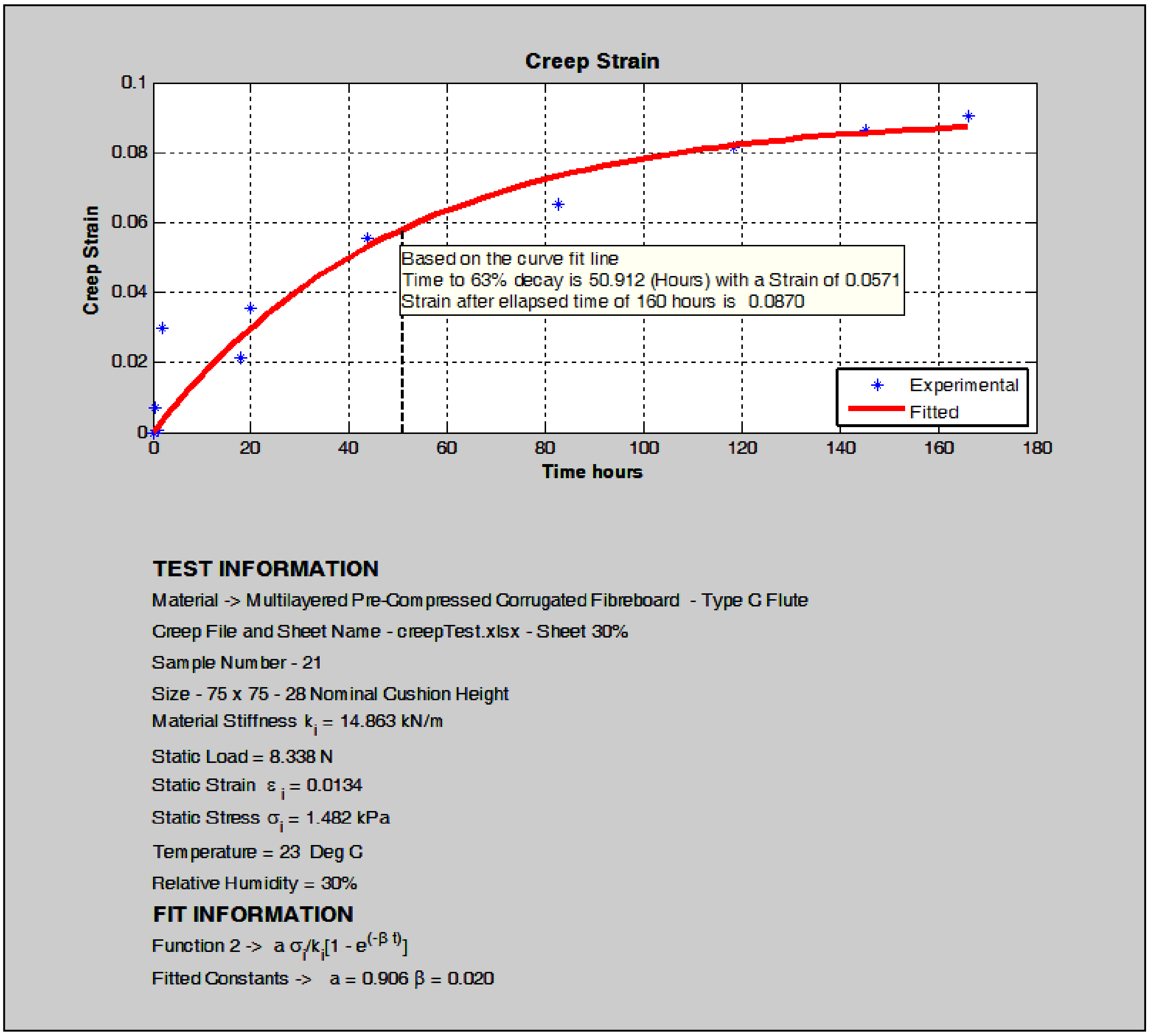


Figure 4.13Creep Experimental and Simulation sample 21 at 30% RH using Equation 4.6

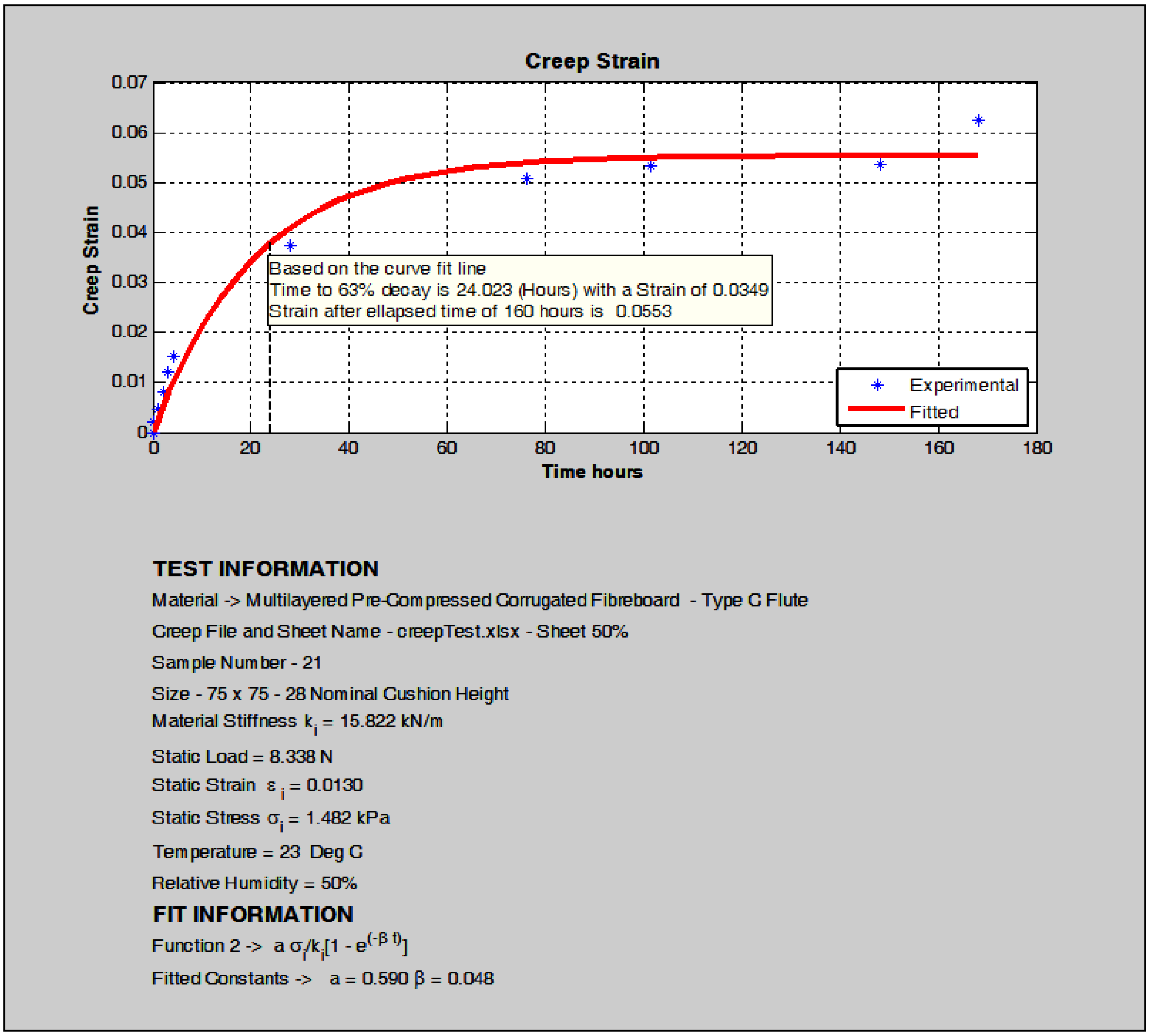


Figure 4.14 Creep Experimental and Simulation sample 21 at 50% RH using Equation 4.6

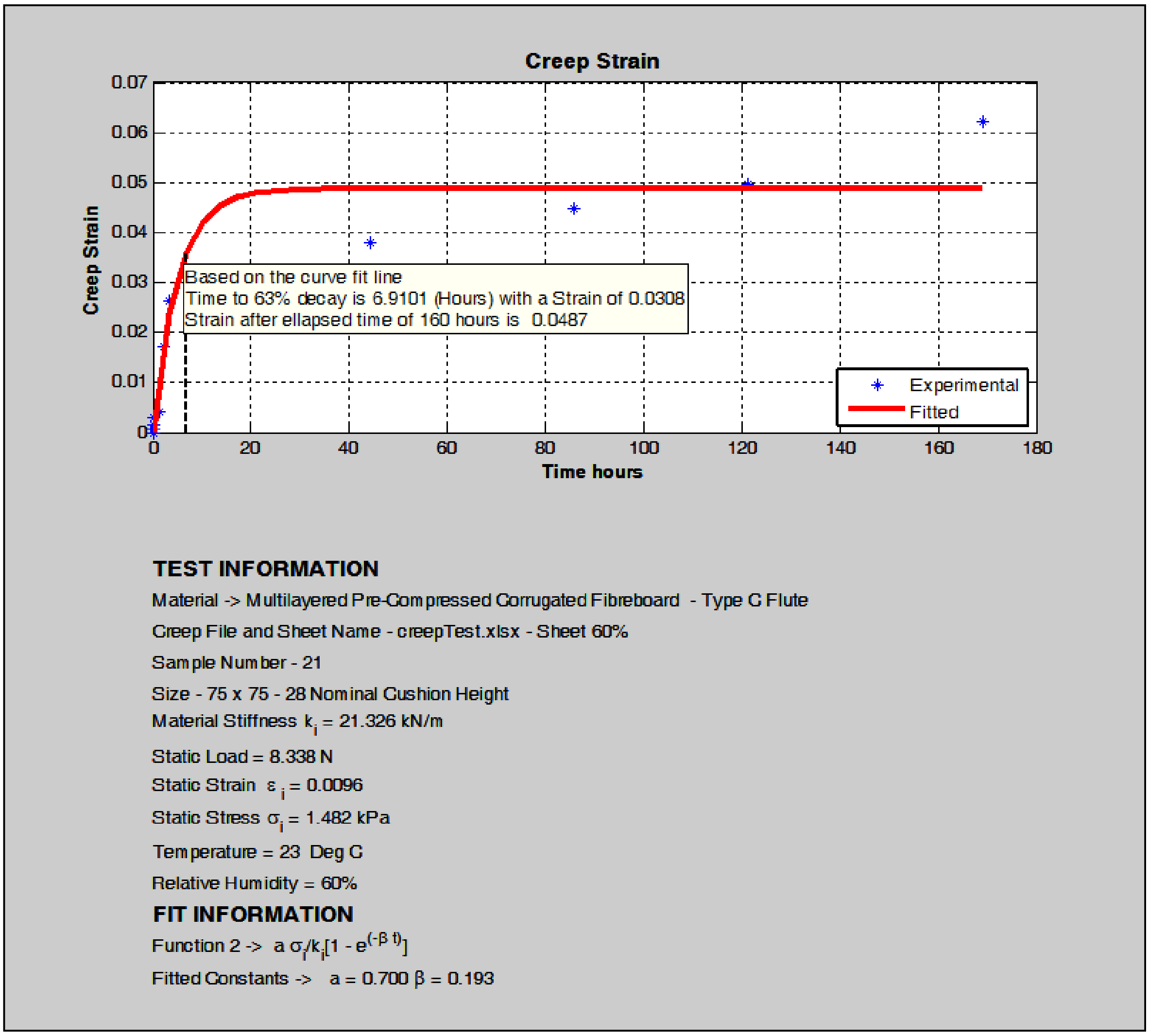


Figure 4.15 Creep Experimental and Simulation sample 21 at 60% RH using Equation 4.6

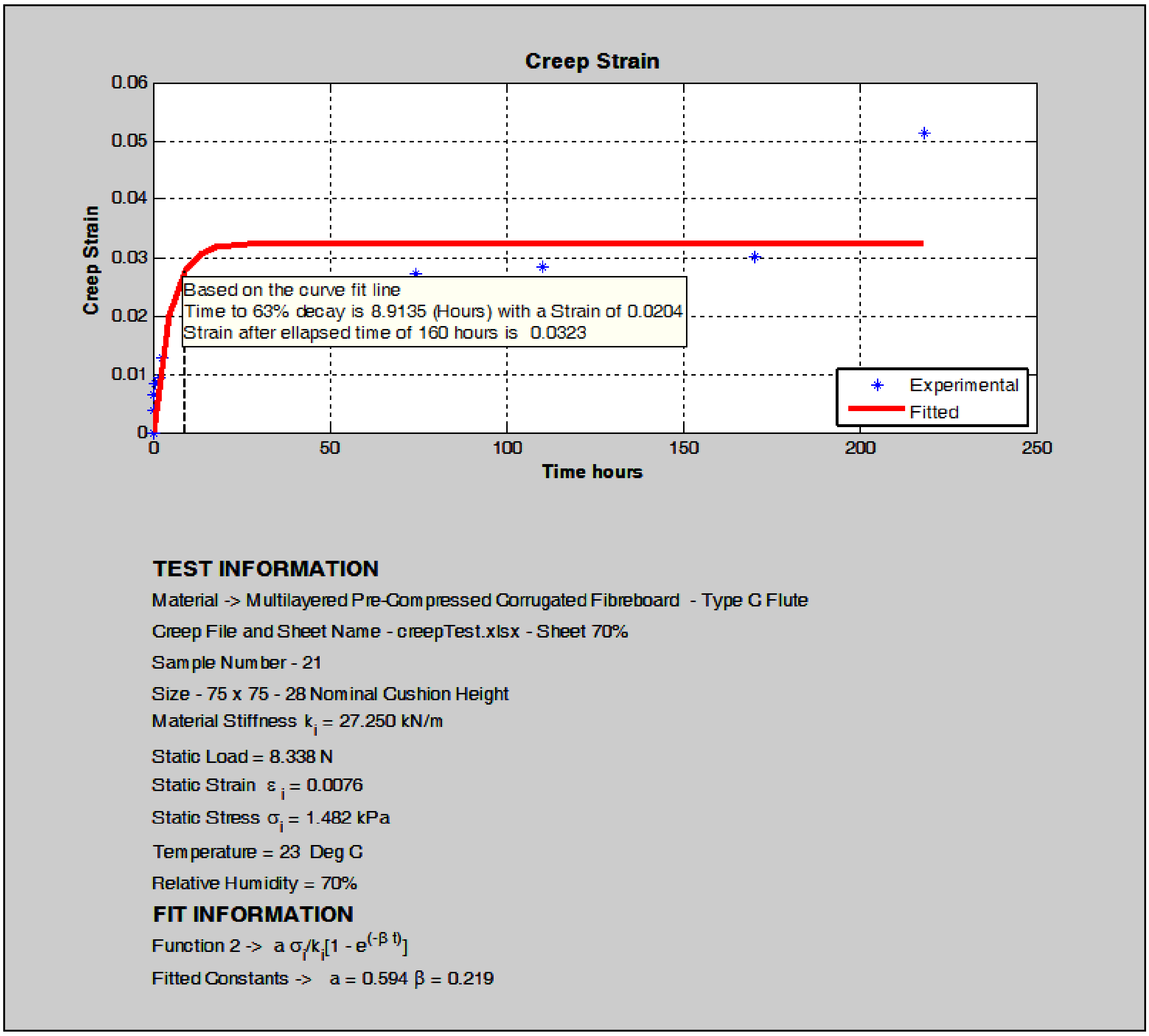


Figure 4.16 Creep Experimental and Simulation sample 21 at 70% RH using Equation 4.6

The results of the experimental and simulated results are shown in the following tables, Table 4-1 and Table 4-2.

Table 4-1 Experimental and Simulated Creep Strain Results for Equation 4.5

Creep Strain Experimental and Analysis Results									
Results based on the variation of Voigt Model									
$\varepsilon_t = a\,\varepsilon_i\left[1-\exp(-t/\tau)\right]$									
		Experimental			Analysis				
Sample	Humidity	Static Strain	Max Time	Max Strain	Multiplier a	Time τ	Time-63% Decay	63% Strain	Strain-160 Hours
	%	Experimental	Hours	Experimental		hours	hours		
21	30	0.0134	166.310	0.0920	6.7380	49.4040	50.9120	0.0571	0.0870
	50	0.0130	168.150	0.0633	4.2310	19.6090	20.5910	0.0347	0.0550
	60	0.0178	169.250	0.0628	2.7140	5.1679	6.9100	0.0306	0.0483
	70	0.0200	170.330	0.0303	1.3550	3.5447	6.9540	0.0171	0.0272
22	30	0.0066	166.310	0.0995	13.7300	19.1960	20.3660	0.0574	0.0908
	50	0.0096	168.150	0.0611	5.5760	6.7417	6.8652	0.0338	0.0536
	60	0.0174	169.250	0.0883	4.5120	33.9920	34.5420	0.0497	0.0780
	70	0.0263	170.330	0.0558	1.7200	6.7505	6.9542	0.0286	0.0453
23	30	0.0086	166.310	0.1112	11.6700	25.9100	27.1540	0.0639	0.1010
	50	0.0092	168.150	0.0509	5.1720	27.7370	30.8660	0.0303	0.0479
	60	0.0174	169.250	0.0788	4.3310	50.8290	51.8120	0.0476	0.0723
	70	0.0201	170.330	0.0274	1.2090	21.6070	24.3330	0.0154	0.0243

Table 4-2 Experimental and Simulated Creep Strain Results for Equation 4.6

Creep Strain Experimental and Analysis Results										
Results based on the variation of Voigt Model										
							$\varepsilon_t = a\frac{\sigma_i}{k_i}\left[1-\exp(-\beta t)\right]$			
		Experimental			Analysis					
Sample	Humidity	Static Strain	Max Time	Max Strain	Static Stiffness	Multiplier a	Multiplier β	Time-63% Decay	63% Strain	Strain-160 Hours
	%	Experimental	Hours	Experimental	kN/m			hours		
21	30	0.0134	166.310	0.0920	14.863	0.906	0.020	50.912	0.0571	0.0870
	50	0.0130	168.150	0.0633	15.822	0.590	0.048	24.023	0.0349	0.0553
	60	0.0178	169.250	0.0628	11.407	0.371	0.193	6.910	0.0305	0.0483
	70	0.0200	170.330	0.0303	10.218	0.220	0.219	8.914	0.0202	0.0319
22	30	0.0066	166.310	0.0995	30.656	1.880	0.051	20.366	0.0574	0.0909
	50	0.0096	168.150	0.0611	20.437	0.739	0.146	6.865	0.0339	0.0536
	60	0.0174	169.250	0.0883	11.407	0.610	0.028	37.996	0.0501	0.0784
	70	0.0263	170.330	0.0558	7.546	0.231	0.144	6.954	0.0287	0.0454
23	30	0.0086	166.310	0.1112	23.357	1.601	0.037	27.154	0.0642	0.1014
	50	0.0092	168.150	0.0509	21.326	0.700	0.033	30.886	0.0307	0.0484
	60	0.0174	169.250	0.0788	11.407	0.581	0.019	51.812	0.0477	0.0724
	70	0.0201	170.330	0.0274	10.218	0.168	0.044	24.334	0.0154	0.0244

To have a better appreciation of the results, the curve fitted graphs are presented as a family of curves in the following Figures 4.17 to 4.22.

The figures are for function 2 – Equation (4.6) firstly showing the curves without the influence of Static Strain and then with the influence of Static Strain. The full list of curves are shown in Appendix C.

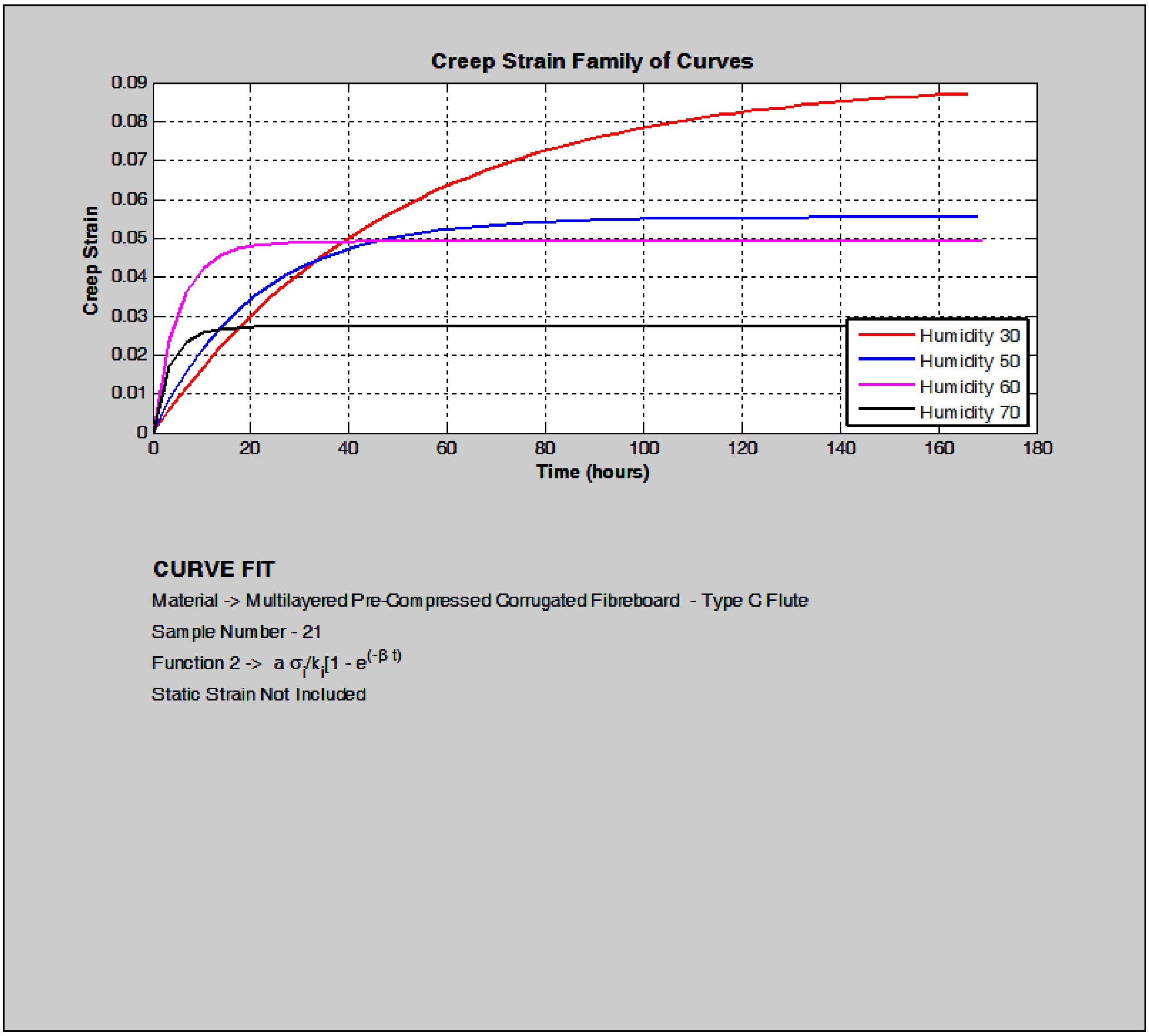


Figure 4.17 Simulated Curve Family for Sample 21 over the experimental Humidity Range, no Static Strain

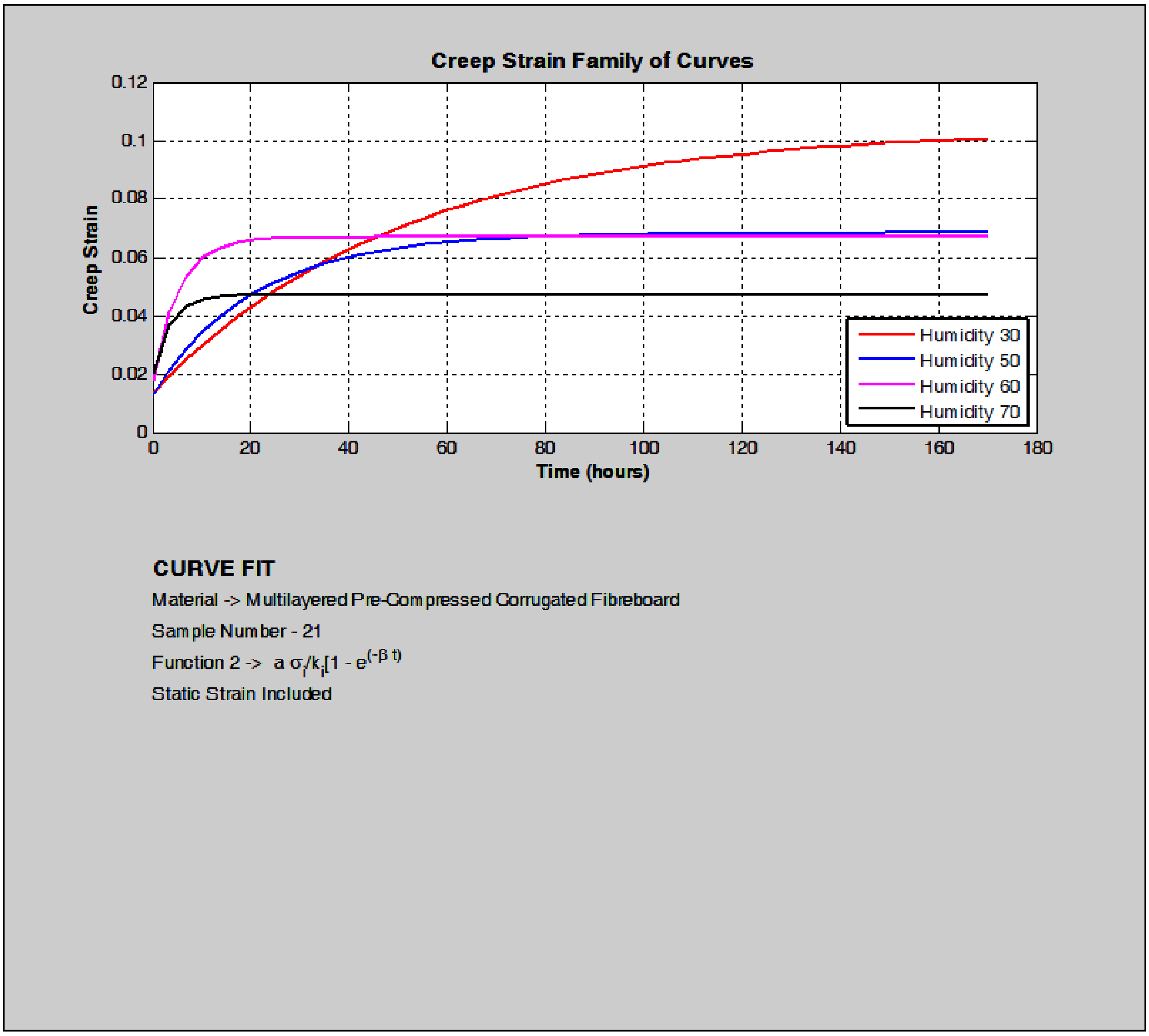


Figure 4.18 Simulated Curve Family for Sample 21 over the experimental Humidity Range, Static Strain

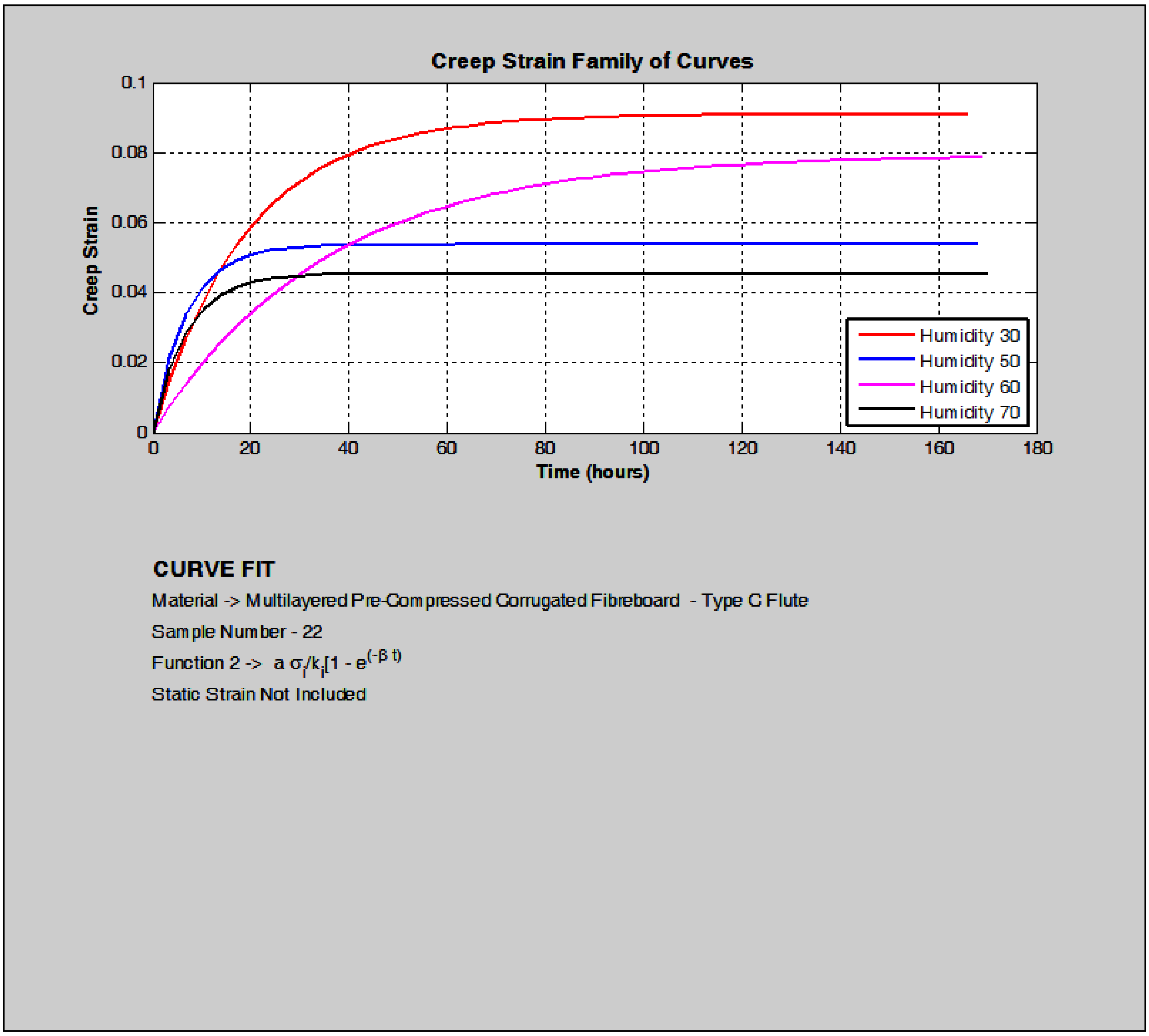


Figure 4.19 Simulated Curve Family for Sample 22 over the experimental Humidity Range, no Static Strain

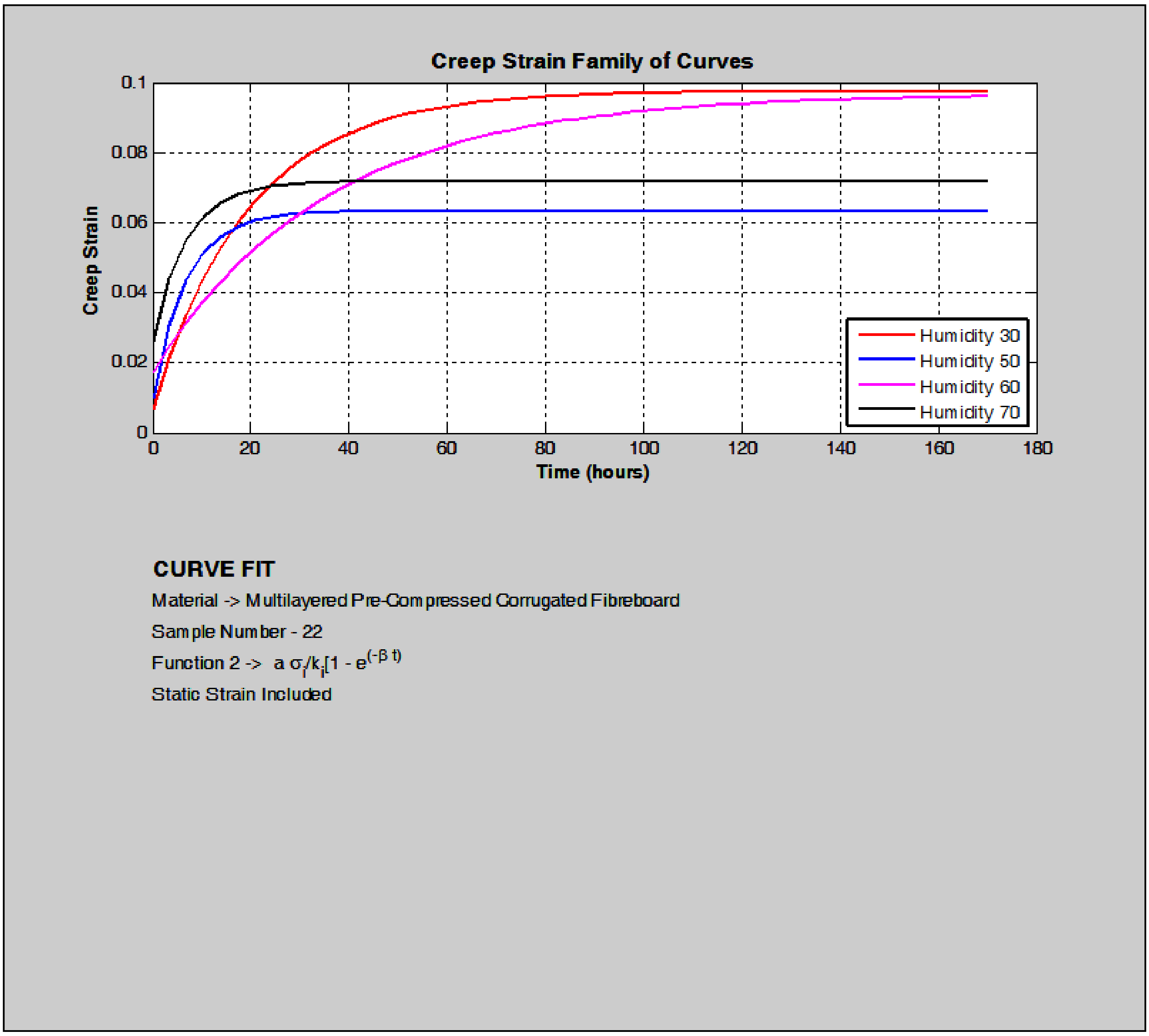


Figure 4.20 Simulated Curve Family for Sample 22 over the experimental Humidity Range, Static Strain

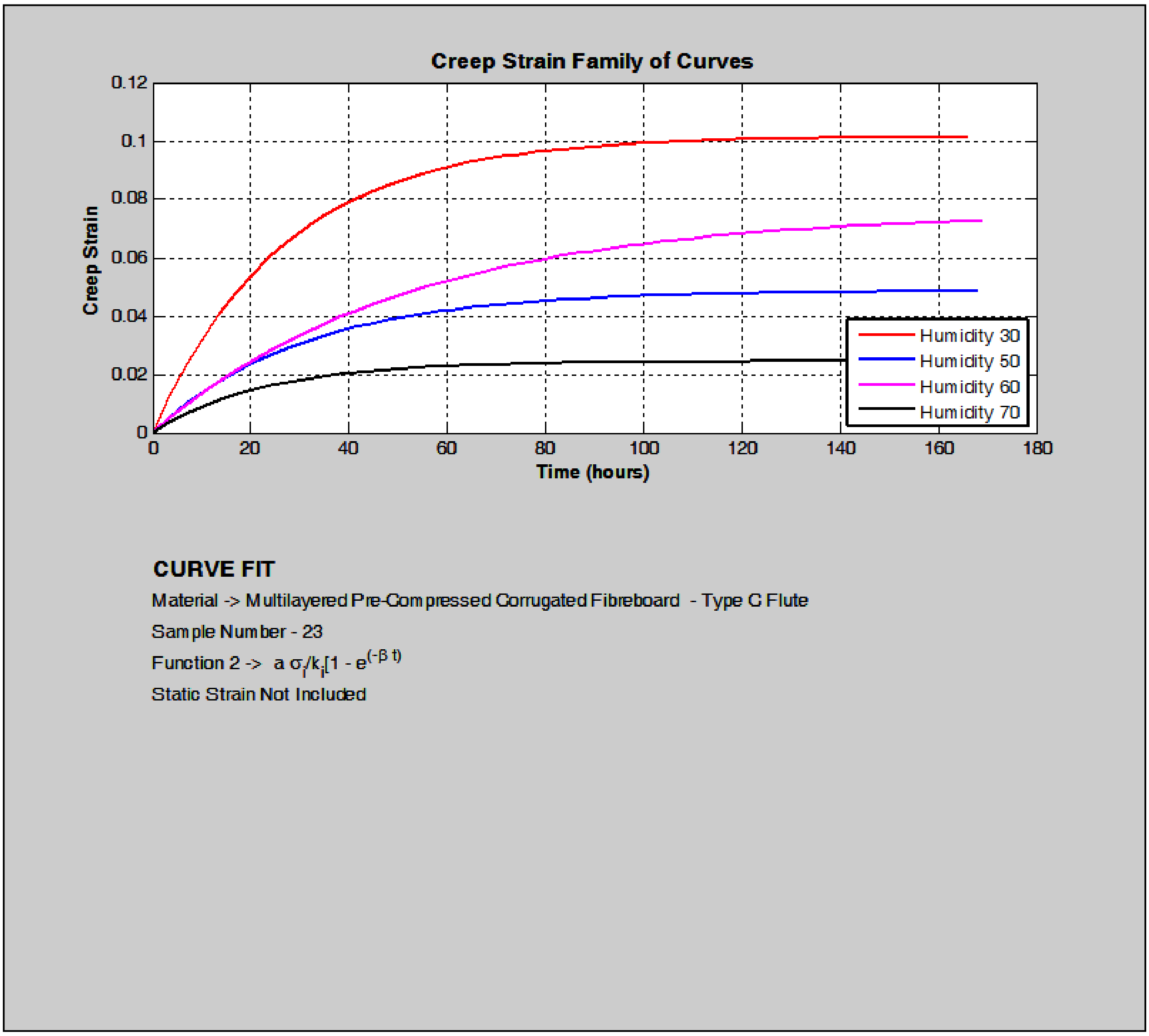


Figure 4.21 Simulated Curve Family for Sample 23 over the experimental Humidity Range, no Static Strain

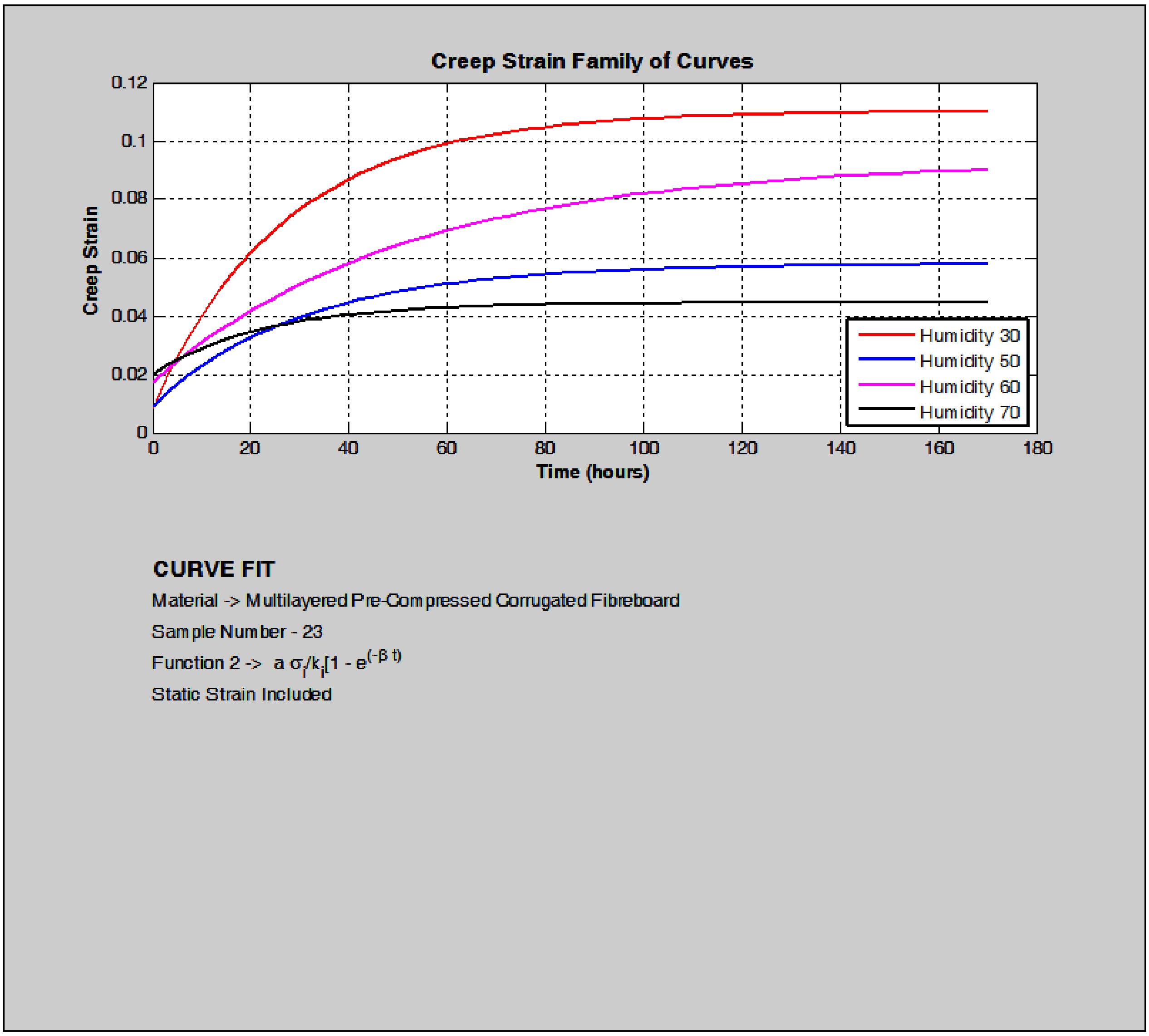


Figure 4.22 Simulated Curve Family for Sample 23 over the experimental Humidity Range, Static Strain

Chapter 5 Discussion and Conclusion

The questions posed for this study of the creep characteristics of multi-layered corrugated fibreboard protective were:

1. What are the cushion static compression characteristics?
2. When subjected to axial load will the cushions suffer time dependent deformation (creep)?
3. If creep is evident can it be modeled with a variation of Voigt Model of Viscoelasticity?
4. What effect does humidity have on the cushions?

5.1 Static Compression

The main reason for conducting static compression testing on the multilayered fibreboard cushions was firstly to crush virgin cushions so that they become pre-compressed. Secondly, was to obtain an appreciation to obtain an appreciation of the static strain and static and stiffness values to help in the design of the creep experiments. However the opportunity has been taken during this study to model the static characteristics. The modeling was based on the following expressions taken from Chapter 4 and repeated here as Equations (5.1) and (5.2).

Compression Model 1

$P1 = F_m\left(1 - e^{-a\varepsilon}\right)$ Phase 1 Elastic

$P2 = SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right)$ Phase 2 Visco-Elastic

$F = P1 + P2$

Therefore

$$F = F_m\left(1 - e^{-a\varepsilon}\right) + SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right) \quad (5.1)$$

Compression Model 2

Phase 1 and 2 Elastic

$P_1 = \delta * SS1$ for $\delta = 0 \rightarrow \delta_A$ and

$P_1 = Force(\delta_A)$ for $\delta = 0 \rightarrow \delta_C$ and

$P_2 = \delta * SS2$ for $\delta = \delta_B \rightarrow \delta_C$ and

Phase 3 Visco-Elastic

$P3 = SF\left(\frac{1}{(\varepsilon_0 - \varepsilon)} - \frac{1}{\varepsilon_0}\right)$

Therefore the simulated force is

$F = P1 + P2 + P3$

δ is the experimental deflection

SS1 and SS2 are the Static Strains

F is the Simulated Force corresponding to Static Strain

(5.2)

The result of this modeling or simulation is shown in Figure 5.1 On inspection of the graph it can be seen that the simulations based on Model 1 and Model 2 can reasonably represent the experimental data. However the need to determine more accurately the material stiffness makes the Model 2 a more arduous task.

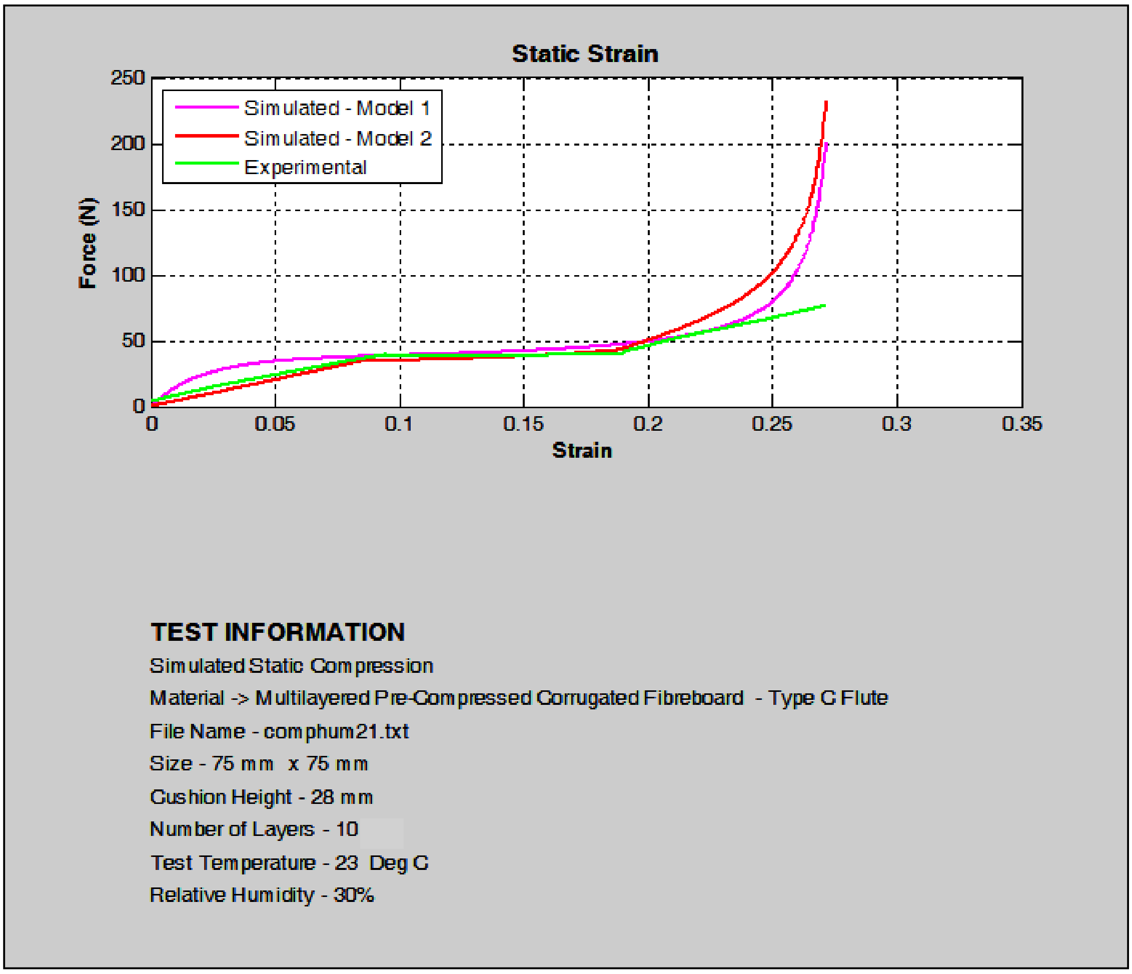


Figure 5.1 Cushion Compression and Simulation at 30% RH using Equation 5.1 and 5.2

The first part of the graph represents the elastic section of the compression testing. The central flat part of the graphs seems to be a layer collapsing mechanism that produces a constant force level despite the continuation of deflection. The end section represents the flattening of the cushion allowing the force to tend to infinity.

5.2 Creep Characteristics

As a preliminary to creep testing it was necessary to pre-condition the cushion test samples. As was stated in Chapter 3, paper board materials take time to absorb moisture. Also stated from the results shown in Table 5.1, are indications that over the conditioning period the cushions absorb moisture between 4.4 to 10.4 percent depending on the set humidity level, taking a time interval between 96 to 180 hours, from zero moisture levels. Conditioning was also carried out to 80%, which took about 240 hours. This level is not shown here as it was discarded from the creep testing analysis because of severe creep problems.

The fact that the conditioning times are slow indicates that as the cushions are tightly compressed moisture may have difficulty fully penetrating, which is a good attribute for protective cushions. The creep experiments carried as in Chapter 3 are summarized in Table 5.2 as the final experimental observations observed.

Table 5-1 Moisture Conditioning times

Weight of Samples at 50% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	37.13	35.22	34.92
1	37.20	35.26	34.95
2	37.23	35.29	34.97
3	37.25	35.30	34.97
48	37.26	35.30	34.97
72	38.71	36.65	36.36
96	38.75	36.71	36.34
Increased Mass	1.62	1.49	1.42
% Increase	4.36	4.23	4.07

Weight of Samples at 60% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	36.80	34.78	34.47
1	37.01	35.00	34.67
2	37.16	35.14	34.81
3	37.27	35.26	34.94
99	37.70	35.65	35.25
147	39.38	37.34	36.98
170	39.25	37.14	36.75
Increased Mass	2.45	2.36	2.28
% Increase	6.66	6.79	6.61

Weight of Samples at 70% RH			
Hours Lapsed (hours)	Weight (grams)		
Sample Number	21	22	23
0	34.94	33.09	32.67
1	35.66	33.80	32.45
2	36.10	34.23	33.88
23	38.01	36.05	35.69
70	38.25	36.18	35.82
119	38.39	36.31	35.91
180	38.56	36.55	36.05
Increased Mass	3.62	3.46	3.38
% Increase	10.36	10.46	10.35

Table 5-2 Experimental Creep Test Results

		Experimental		
Sample	Humidity	Static Strain	Max Time	Max Strain
	%	Experimental	Hours	Experimental
21	30	0.0134	166.310	0.092
	50	0.0130	168.150	0.0633
	60	0.0178	169.250	0.0628
	70	0.0200	170.330	0.0303
22	30	0.0066	166.310	0.0995
	50	0.0096	168.150	0.0611
	60	0.0174	169.250	0.0883
	70	0.0263	170.330	0.0558
23	30	0.0086	166.310	0.1112
	50	0.0092	168.150	0.0509
	60	0.0174	169.250	0.0788
	70	0.0201	170.330	0.0274

There is an unexpected result in that the creep strain levels tend to be lower as the humidity level rises. For instance for the 70% humidity level at a longer time zone the creep values are lower than that of 60%. This opens up the question does this material stiffen up at higher humidity levels, this was not apparent during static compression testing. On the contrary the stiffness seemed to be of lower values as the moisture level increased. It must be pointed out that static compression testing was conducted in the open air after being conditioned. However the experimental static strain during creep testing is higher, at higher humidity levels that seems to indicate that the initial push at when the load is applied is higher at the elevated humidity levels. This could partly account for the increase in creep strain at higher humidity levels.

5.3. Creep Modeling

Curve fitting Analysis was carried out to determine whether the experimental data could be fitted to a modified Voigt model for Viscoelasticity and obtain the appropriate constants and exponents. The models are repeated here as Equations (5.3) and (5.4).

Function 1

$$\varepsilon_t = a\,\varepsilon_i\left[1-\exp\left(-t/\tau\right)\right] \tag{5.3}$$

where a is an experimental multiplier of the static Strain ε_i

and τ is the relaxation time

Function 2

$$\varepsilon_t = a\frac{\sigma_i}{k_i}\left[1-\exp\left(-\beta t\right)\right] \tag{5.4}$$

where a and β are experimental multipliers

σ_i is the Static Stress

k_i is the Static Stiffness

Typical curve fitting results using Function 1 and Function 2 at 30% humidity are shown in Figures 5.2 and 5.3. The resulting curve show very little difference between them. The full curve fitting results are shown in

Table 5-3 and Table 5-4

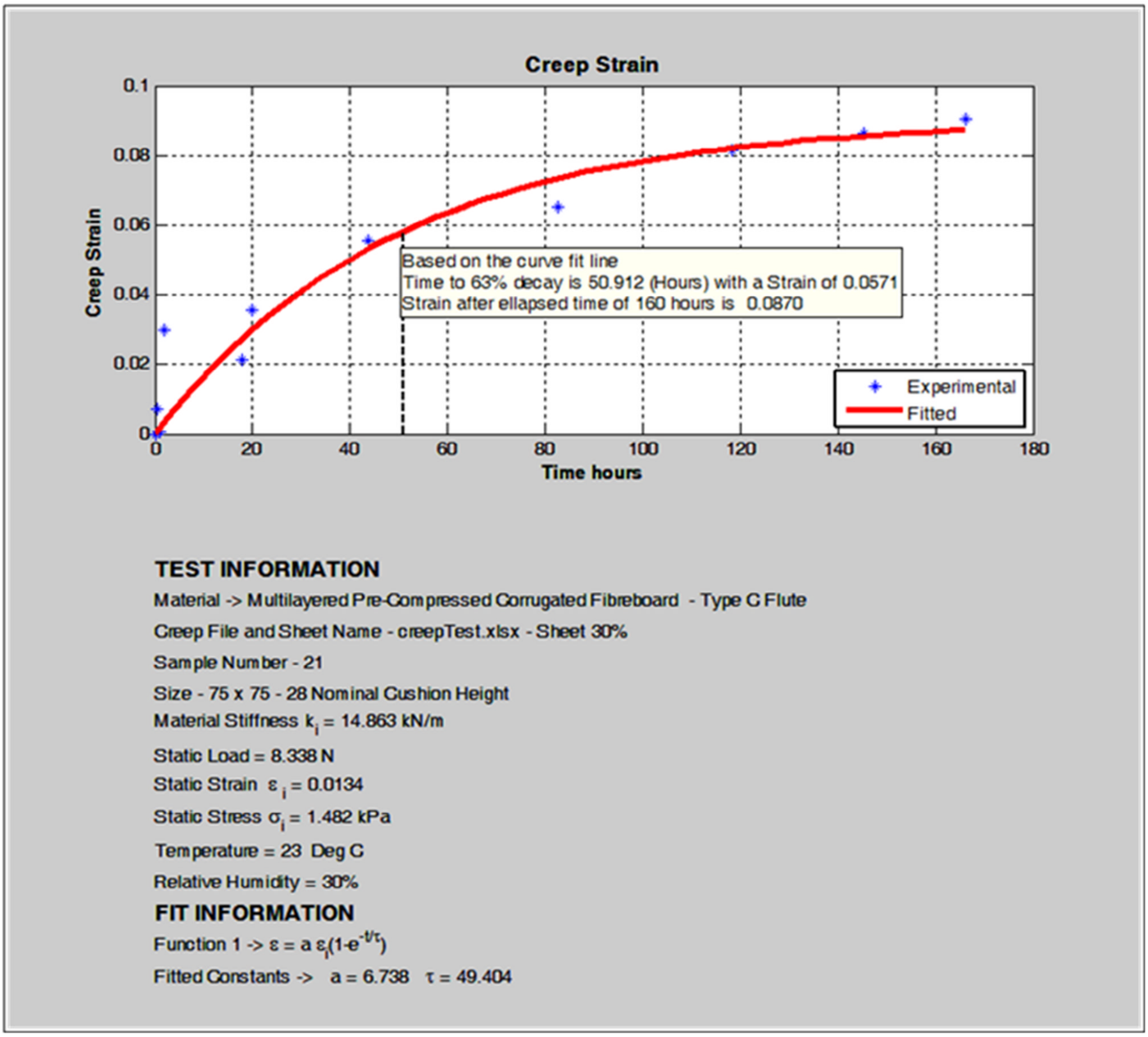


Figure 5.2 Typical Curve Fitting for sample 21 using equation 5.3

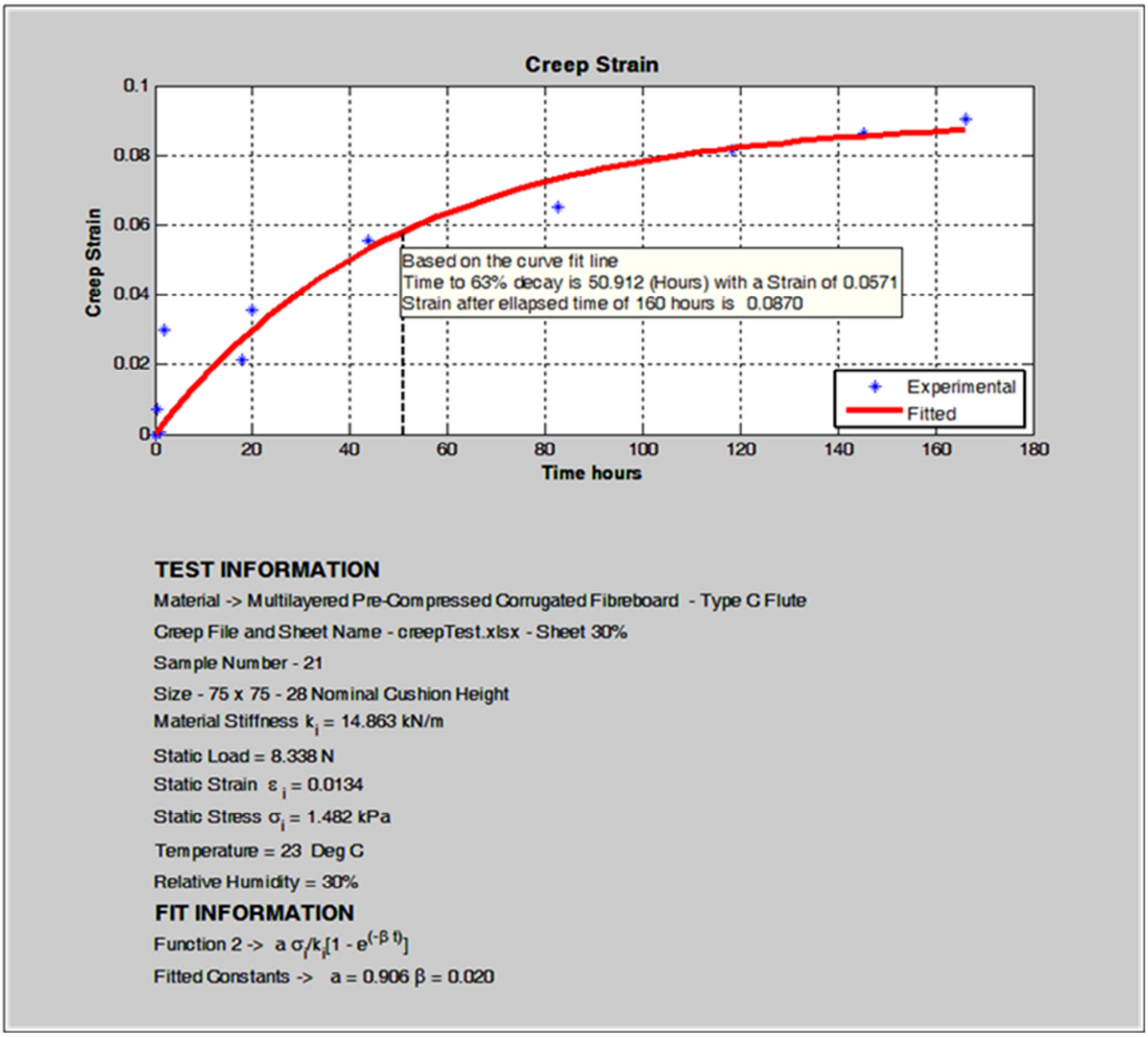


Figure 5.3 Typical Curve Fitting for sample 21 using equation 5.4

Table 5-3 Creep Strain Analysis for Equation 5.2

Creep Strain Experimental and Analysis Results									
Results based on the variation of Voigt Model									
$\varepsilon_t = a\,\varepsilon_i\left[1-\exp\left(-t/\tau\right)\right]$									
		Experimental			Analysis				
Sample	Humidity	Static Strain	Max Time	Max Strain	Multiplier a	Time τ	Time-63% Decay	63% Strain	Strain-160 Hours
	%	Experimental	Hours	Experimental		hours	hours		
21	30	0.0134	166.310	0.0920	6.7380	49.4040	50.9120	0.0571	0.0870
	50	0.0130	168.150	0.0633	4.2310	19.6090	20.5910	0.0347	0.0550
	60	0.0178	169.250	0.0628	2.7140	5.1679	6.9100	0.0306	0.0483
	70	0.0200	170.330	0.0303	1.3550	3.5447	6.9540	0.0171	0.0272
22	30	0.0066	166.310	0.0995	13.7300	19.1960	20.3660	0.0574	0.0908
	50	0.0096	168.150	0.0611	5.5760	6.7417	6.8652	0.0338	0.0536
	60	0.0174	169.250	0.0883	4.5120	33.9920	34.5420	0.0497	0.0780
	70	0.0263	170.330	0.0558	1.7200	6.7505	6.9542	0.0286	0.0453
23	30	0.0086	166.310	0.1112	11.6700	25.9100	27.1540	0.0639	0.1010
	50	0.0092	168.150	0.0509	5.1720	27.7370	30.8660	0.0303	0.0479
	60	0.0174	169.250	0.0788	4.3310	50.8290	51.8120	0.0476	0.0723
	70	0.0201	170.330	0.0274	1.2090	21.6070	24.3330	0.0154	0.0243

Table 5-4 Creep Strain Analysis for Equation 5.3

Creep Strain Experimental and Analysis Results										
Results based on the variation of Voigt Model										
$\varepsilon_t = a\dfrac{\sigma_i}{k_i}\left[1-\exp\left(-\beta t\right)\right]$										
		Experimental			Analysis					
Sample	Humidity	Static Strain	Max Time	Max Strain	Static Stiffness	Multiplier a	Multiplier β	Time-63% Decay	63% Strain	Strain-160 Hours
	%	Experimental	Hours	Experimental	kN/m			hours		
21	30	0.0134	166.310	0.0920	14.863	0.906	0.020	50.912	0.0571	0.0870
	50	0.0130	168.150	0.0633	15.822	0.590	0.048	24.023	0.0349	0.0553
	60	0.0178	169.250	0.0628	11.407	0.371	0.193	6.910	0.0305	0.0483
	70	0.0200	170.330	0.0303	10.218	0.220	0.219	8.914	0.0202	0.0319
22	30	0.0066	166.310	0.0995	30.656	1.880	0.051	20.366	0.0574	0.0909
	50	0.0096	168.150	0.0611	20.437	0.739	0.146	6.865	0.0339	0.0536
	60	0.0174	169.250	0.0883	11.407	0.610	0.028	37.996	0.0501	0.0784
	70	0.0263	170.330	0.0558	7.546	0.231	0.144	6.954	0.0287	0.0454
23	30	0.0086	166.310	0.1112	23.357	1.601	0.037	27.154	0.0642	0.1014
	50	0.0092	168.150	0.0509	21.326	0.700	0.033	30.886	0.0307	0.0484
	60	0.0174	169.250	0.0788	11.407	0.581	0.019	51.812	0.0477	0.0724
	70	0.0201	170.330	0.0274	10.218	0.168	0.044	24.334	0.0154	0.0244

There are some time variations on samples 22 and 23 however the curve fitting tends to back up the assertions made in section 5.2, the higher the humidity level the quicker the creep strain level converges on the 63% level and the 160 hour level.

A family of curves based on the curve fitting that was created in Chapter 4 for sample 21 using Function 2 is shown here as Figures 5.4. It can be seen more clearly here that curves for 30% humidity show a higher Creep Strain value than that for higher humidity levels. Considering the family of curves in Figure 5.5 when static strain is included the difference between the curves is reduced. There is however still the fact that the higher the humidity the lower the creep strain effect.

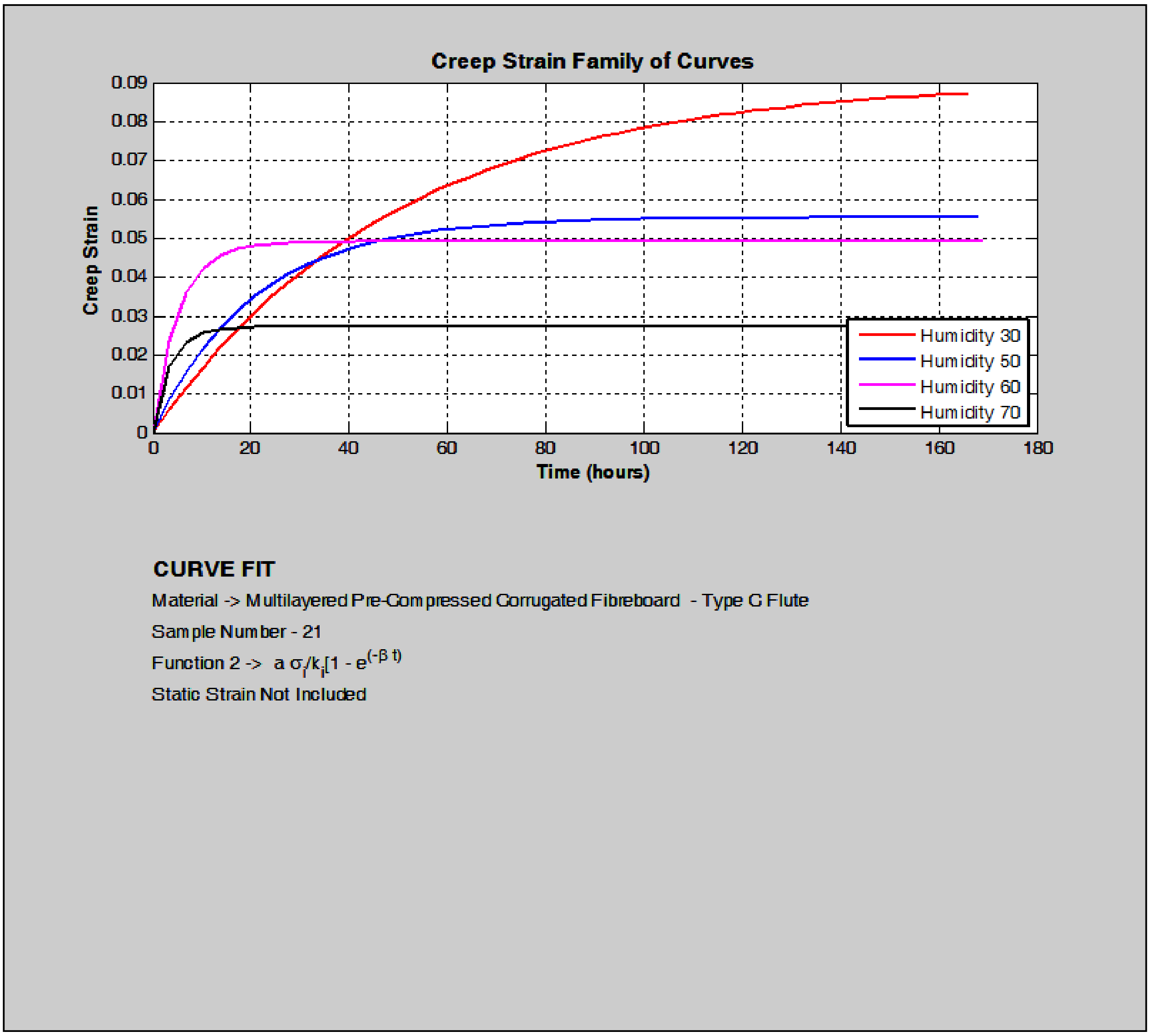


Figure 5.4 Simulated Curve Family for Sample 21 using Function 2 with no Static Strain

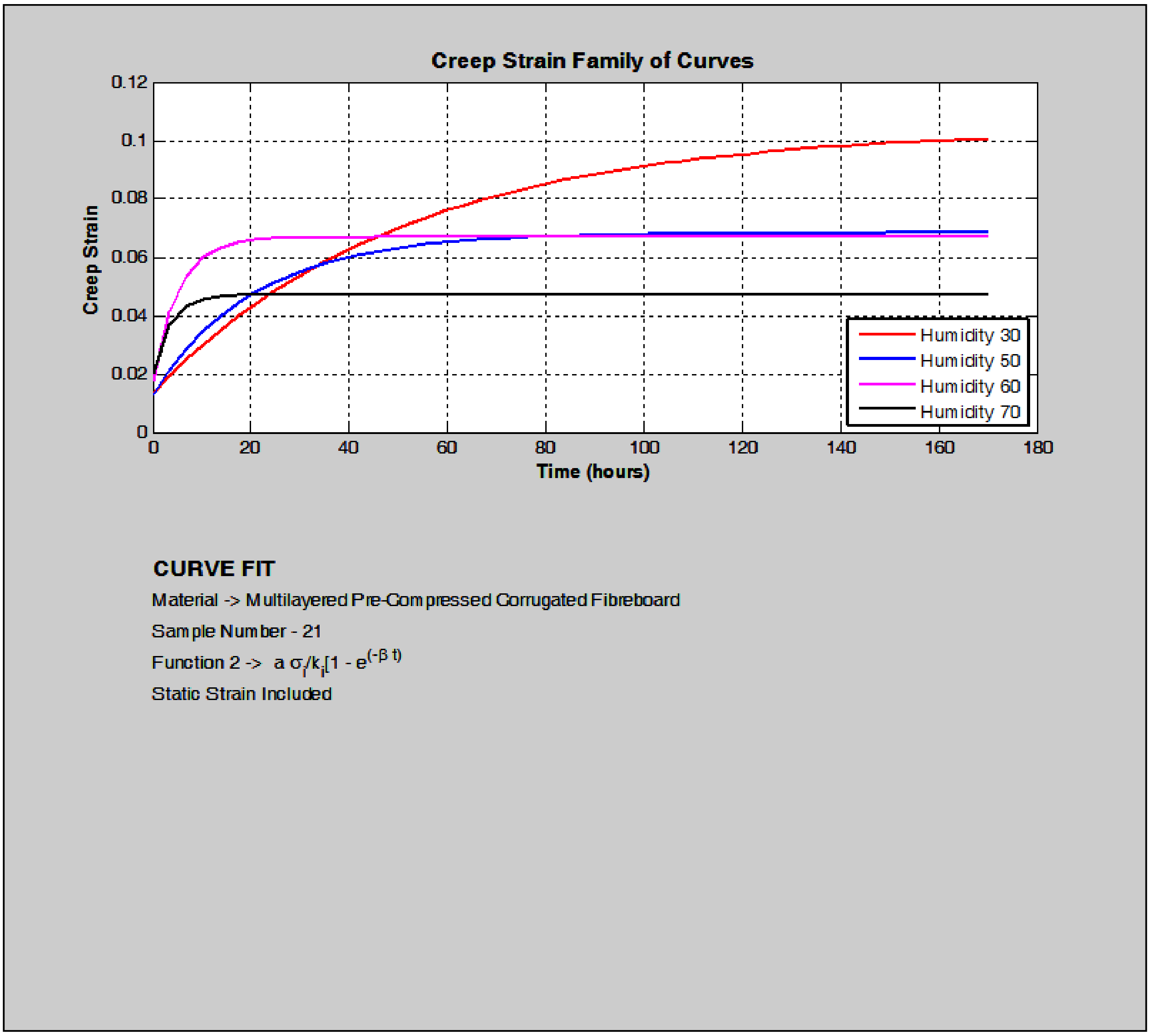


Figure 5.5 Simulated Curve Family for Sample 21 using Function 2 with Static Strain

5.4. Summarizing Remarks

The main thrust of this study was to understand the Time Dependent Deformation or Creep of multi-layered pre-compressed corrugated fibreboard protective cushions at various humidity levels. A variation of the Voigt Model of Visco-Elasticity was presented and used as a curve fit expression against experimental data taken from creep tests. The experimental and curve fit data show that as the humidity level is raised the resulting creep strain is lower, although partly offset by initial or static strain, which is higher at the higher humidity level. The result of having a higher strain at lower humidity levels seems unusual. It could be a result of strain hardening of the glue that secures the layers. The models developed and results presented will assist in the design of protective packaging and produce predictive tools for use in the packaging industry.

The models from this research will help better predict the effects of current and new paper corrugated materials for packaging applications, when exposed to high humidity and long term storage such as in tropical warehouses.

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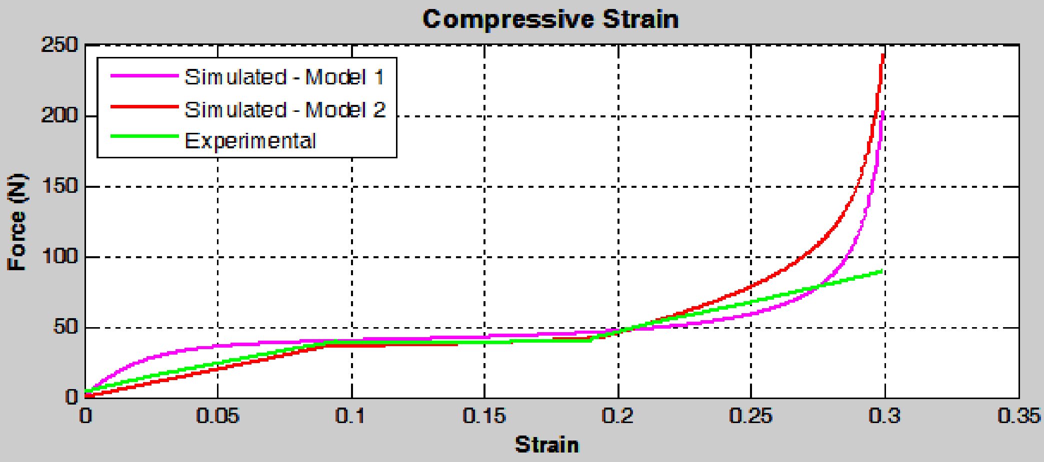
Appendix A

Compression Models Graphs

30 % Humidity



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum21.txt

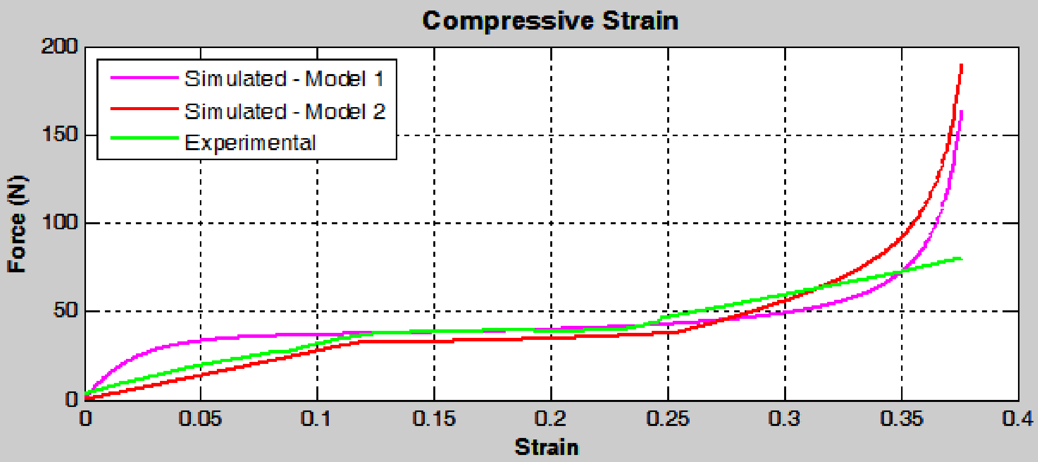
Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 30%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum22.txt

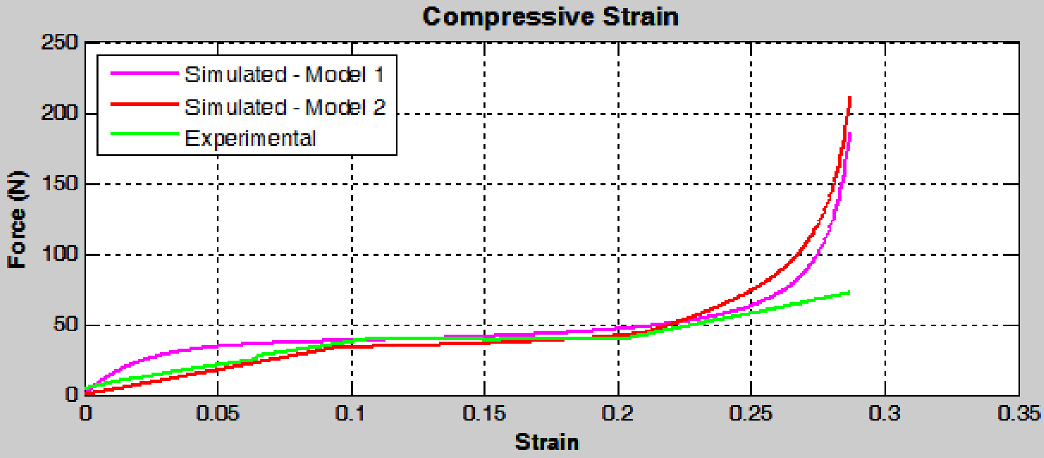
Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 30%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum23.txt

Size - 75 mm x 75 mm

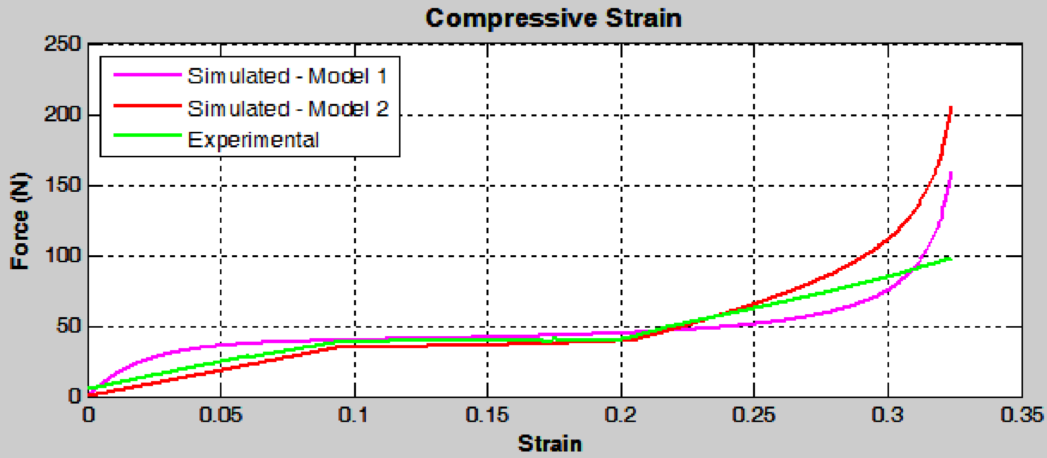
Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 30%

50 % Humidity



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum21.txt

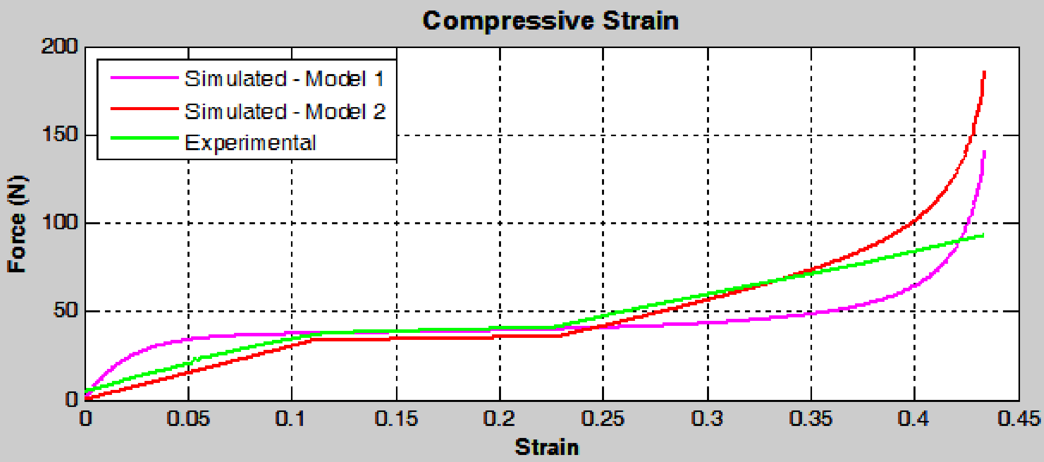
Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 50%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum22.txt

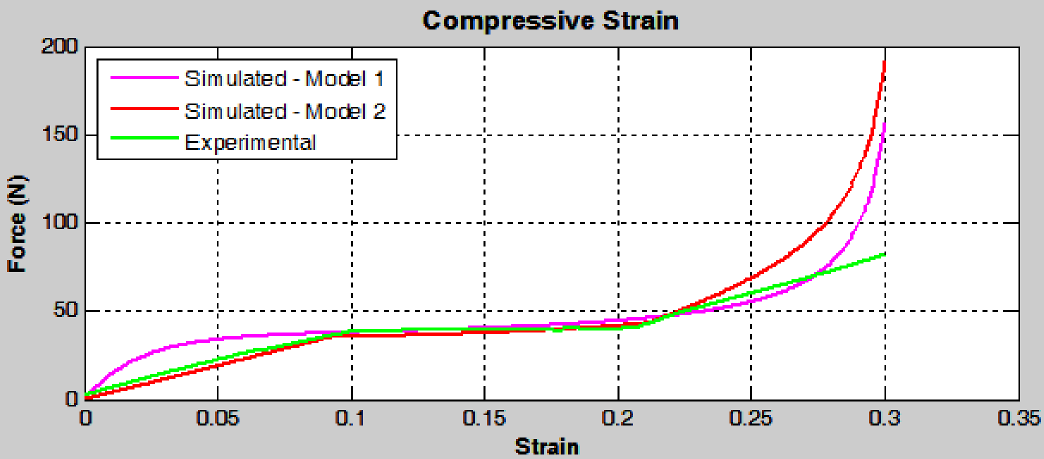
Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 50%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum23.txt

Size - 75 mm x 75 mm

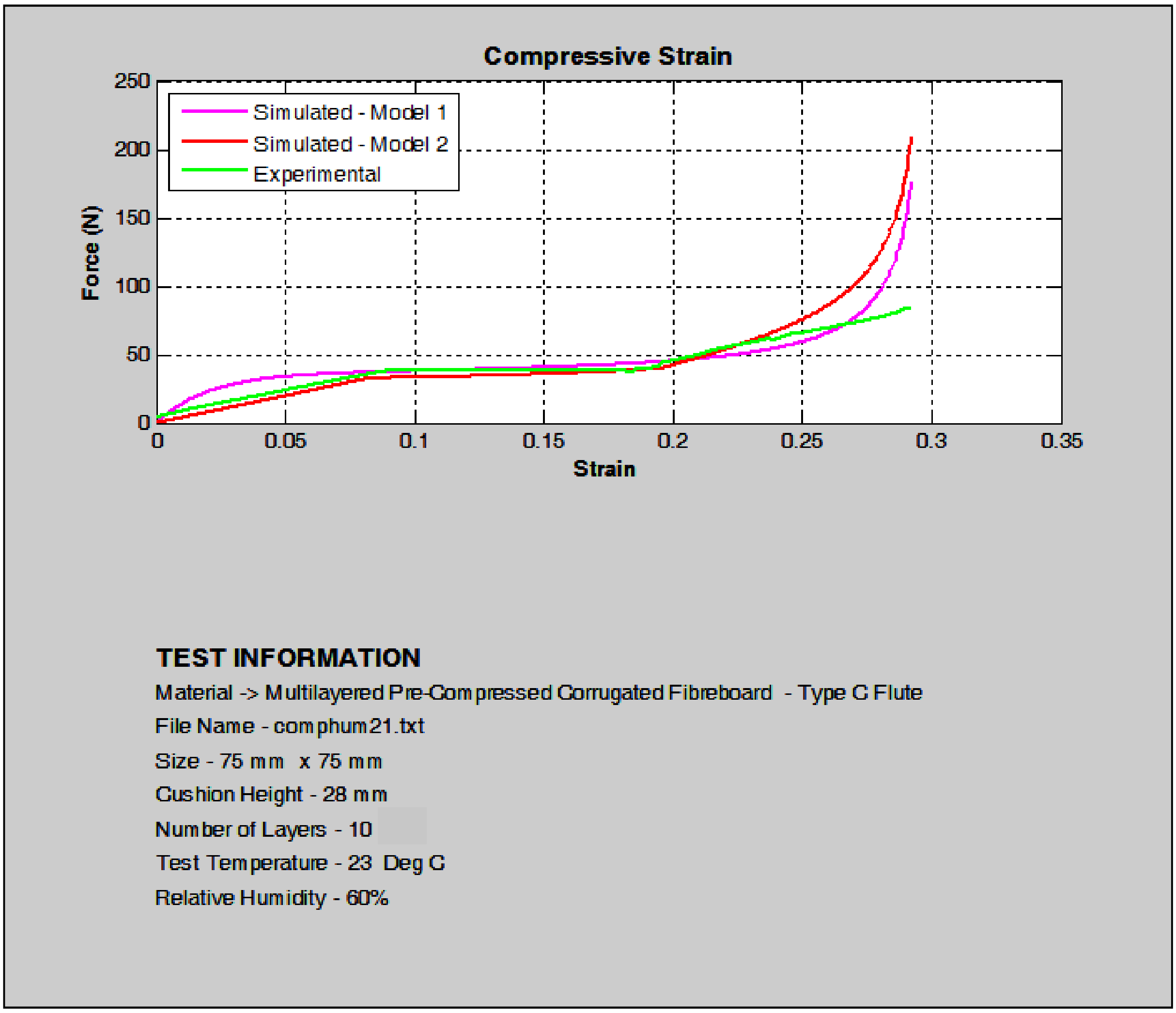
Cushion Height - 28 mm

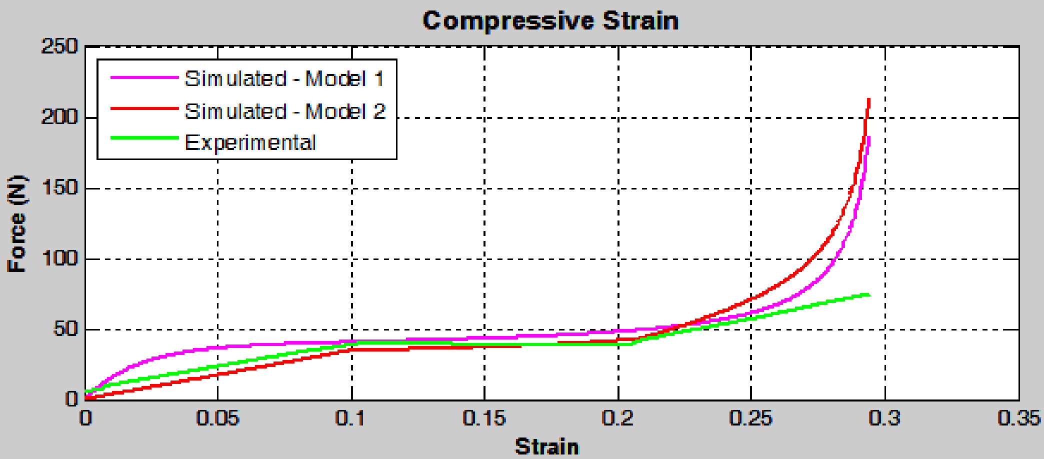
Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 50%

60% Humidity


Compressive Strain
Force (N)
Strain
0
50
100
150
200
250
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Simulated - Model 1
Simulated - Model 2
Experimental
TEST INFORMATION
Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute
File Name - comphum21.txt
Size - 75 mm x 75 mm
Cushion Height - 28 mm
Number of Layers - 10
Test Temperature - 23 Deg C
Relative Humidity - 60%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum23.txt

Size - 75 mm x 75 mm

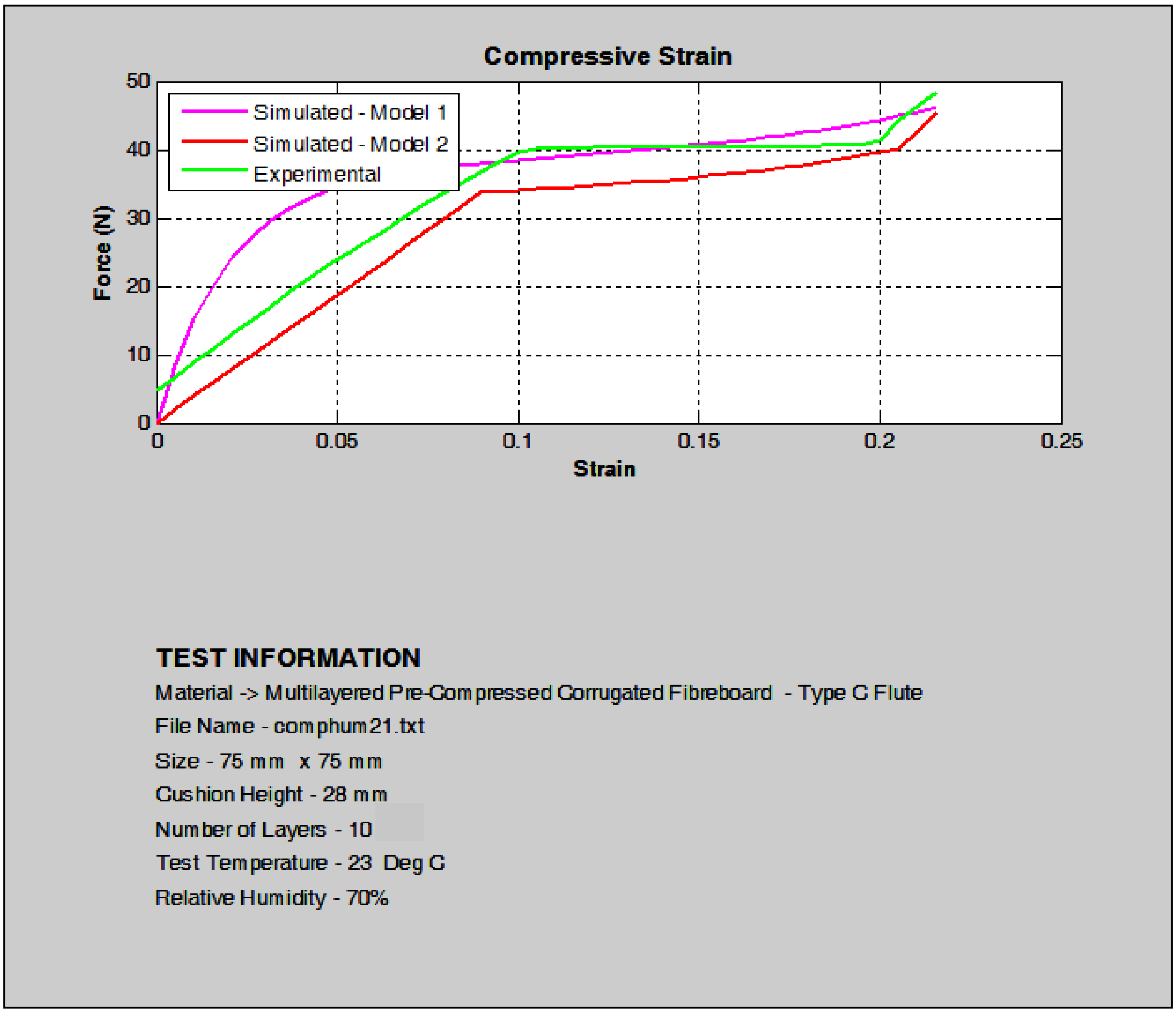
Cushion Height - 28 mm

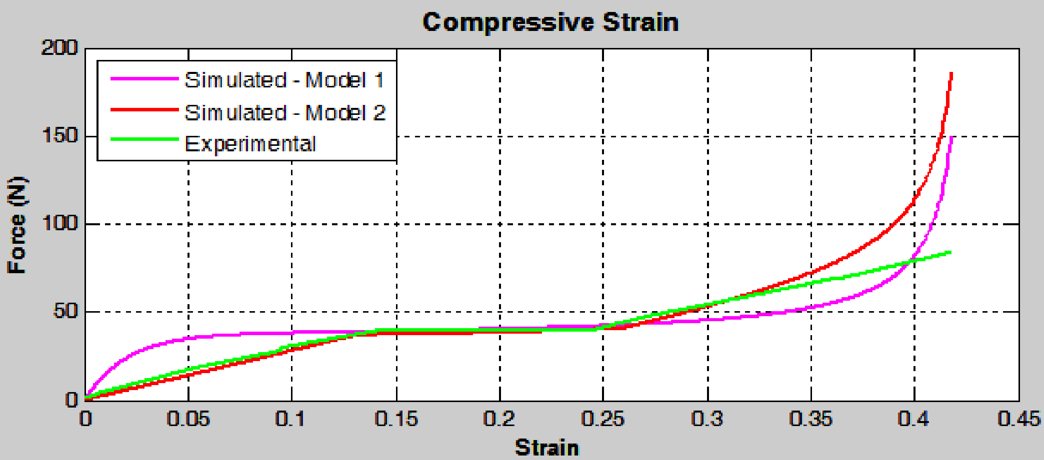
Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 60%

70% Humidity


Compressive Strain
Simulated - Model 1
Simulated - Model 2
Experimental
Force (N)
Strain
0
10
20
30
40
50
0
0.05
0.1
0.15
0.2
0.25
TEST INFORMATION
Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute
File Name - comphum21.txt
Size - 75 mm x 75 mm
Cushion Height - 28 mm
Number of Layers - 10
Test Temperature - 23 Deg C
Relative Humidity - 70%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum22.txt

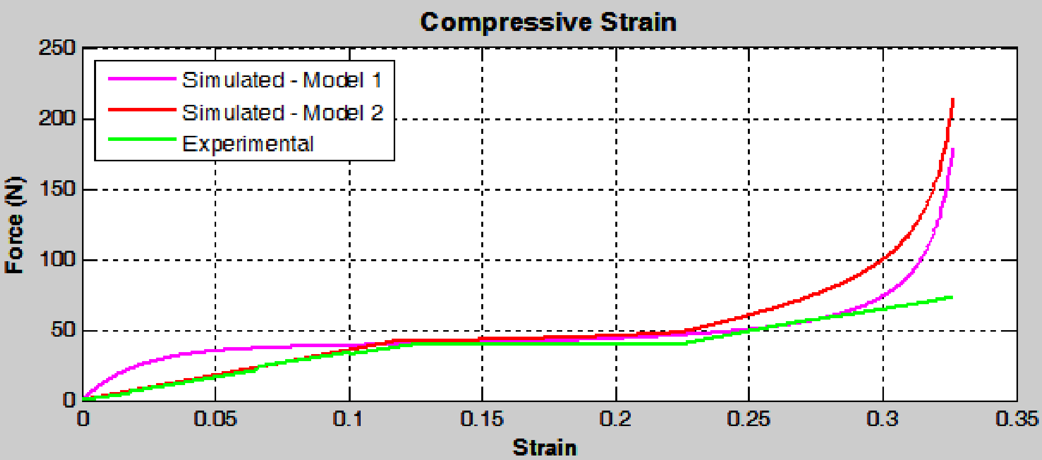
Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

Test Temperature - 23 Deg C

Relative Humidity - 70%



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

File Name - comphum23.txt

Size - 75 mm x 75 mm

Cushion Height - 28 mm

Number of Layers - 10

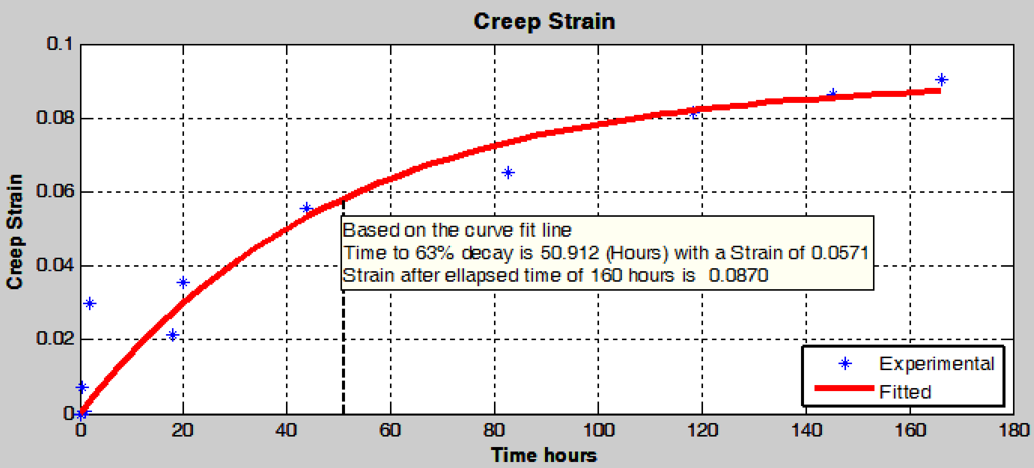
Test Temperature - 23 Deg C

Relative Humidity - 70%

Appendix B

Curve Fitting Graphs

Function 1



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 14.863 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0134

Static Stress σ_i = 1.482 kPa

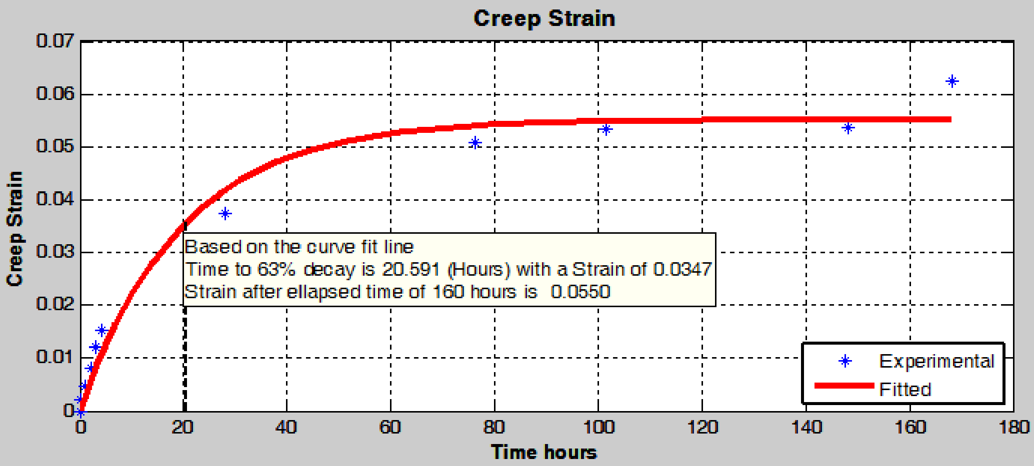
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 6.738 τ = 49.404



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 15.822 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0130

Static Stress σ_i = 1.482 kPa

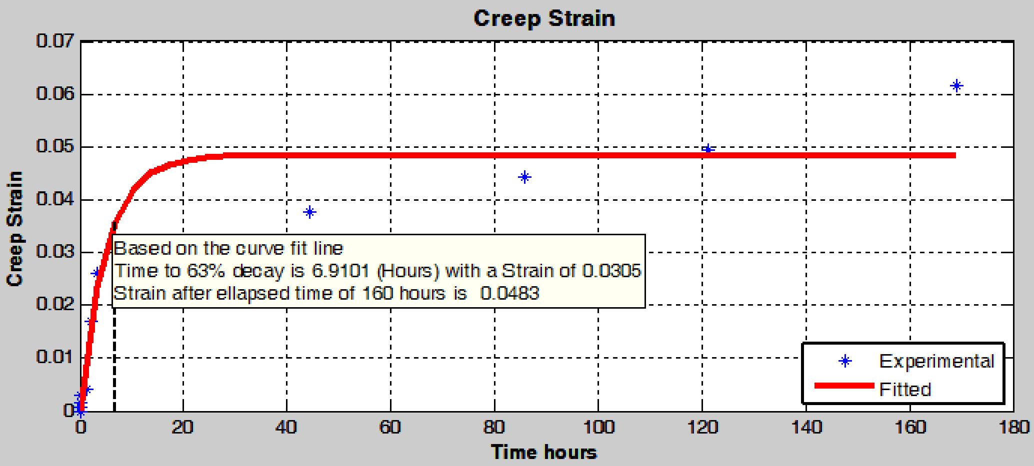
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> $a = 4.231$ $\tau = 19.609$



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0178

Static Stress σ_i = 1.482 kPa

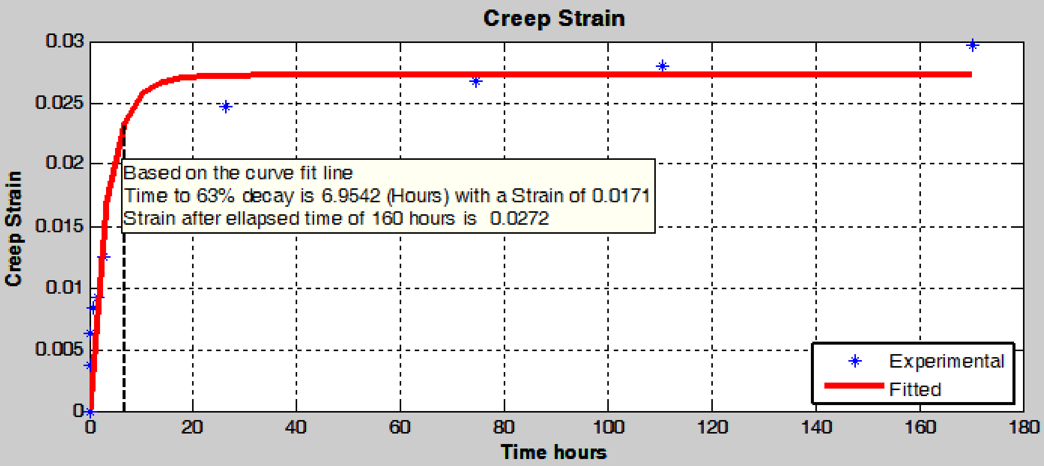
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 2.714 τ = 5.1679



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 10.218 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0200

Static Stress σ_i = 1.482 kPa

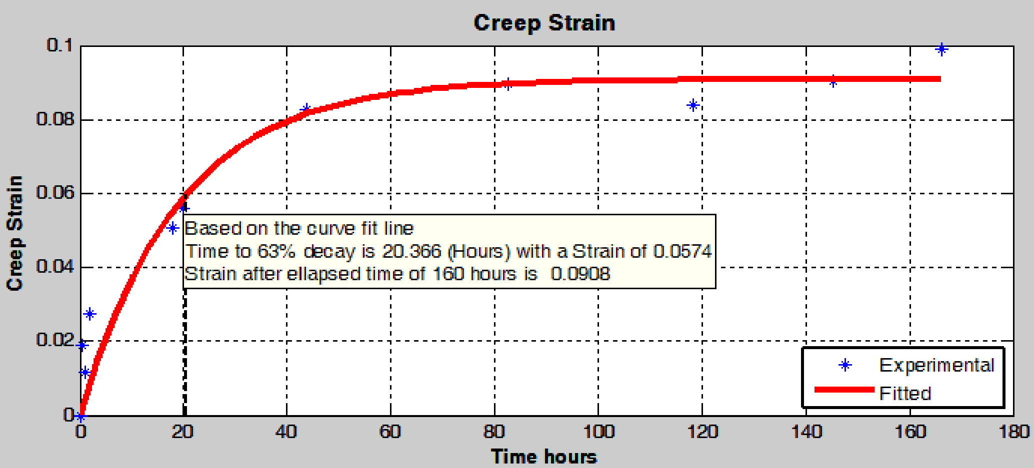
Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 1.355 τ = 3.5447



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 30.656 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0066

Static Stress σ_i = 1.482 kPa

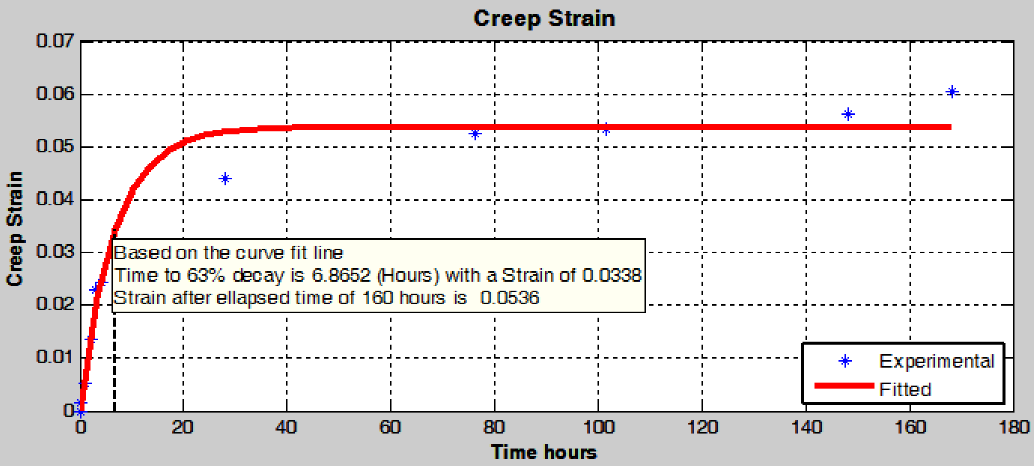
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 13.73 τ = 19.196



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 20.437 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0096

Static Stress σ_i = 1.482 kPa

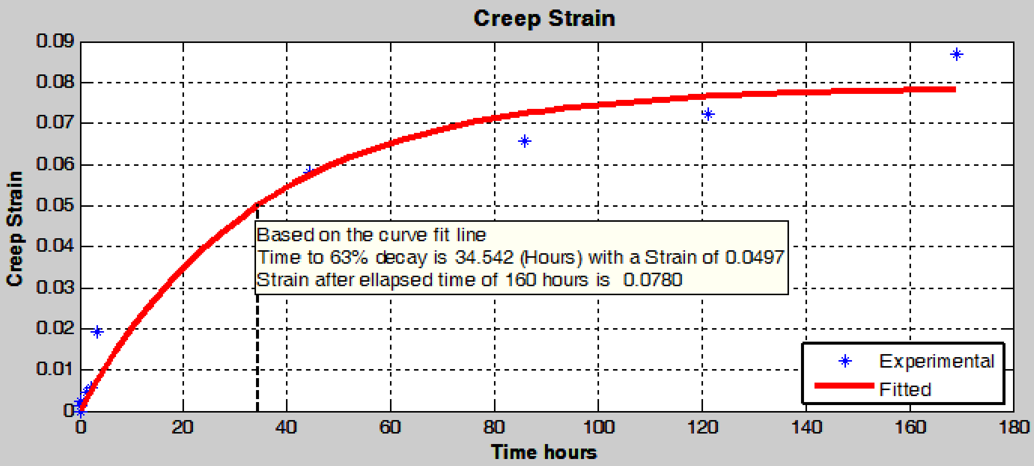
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 5.576 τ = 6.7417



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0174

Static Stress σ_i = 1.482 kPa

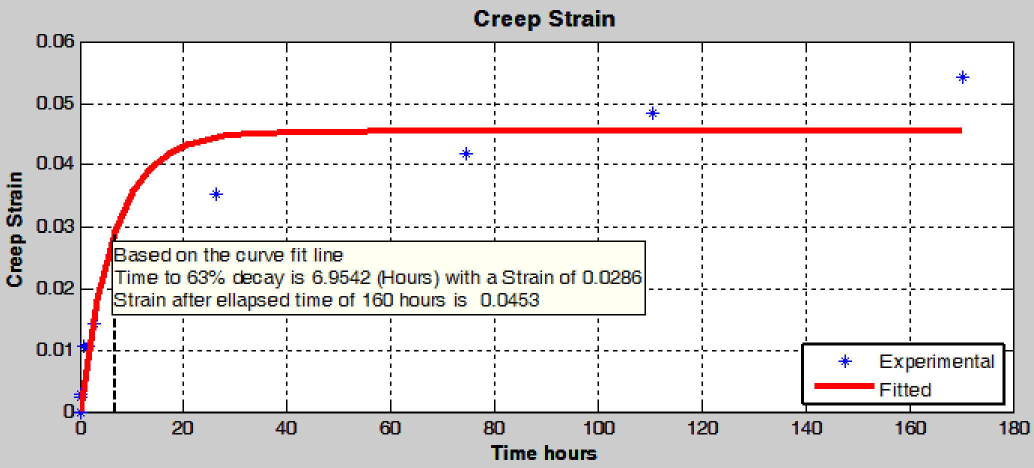
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 1 -> $\varepsilon = a\, \varepsilon_i(1\text{-}e^{-t/\tau})$

Fitted Constants -> a = 4.512 τ = 33.992



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 7.5462 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0263

Static Stress σ_i = 1.482 kPa

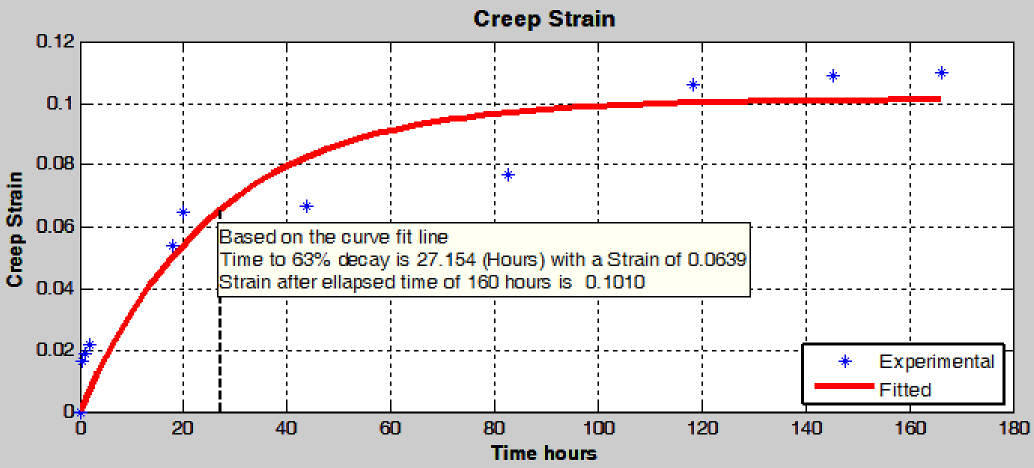
Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

Function 1 -> $\varepsilon = a\, \varepsilon_i (1-e^{-t/\tau})$

Fitted Constants -> a = 1.720 τ = 6.7505



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 23.357 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0086

Static Stress σ_i = 1.482 kPa

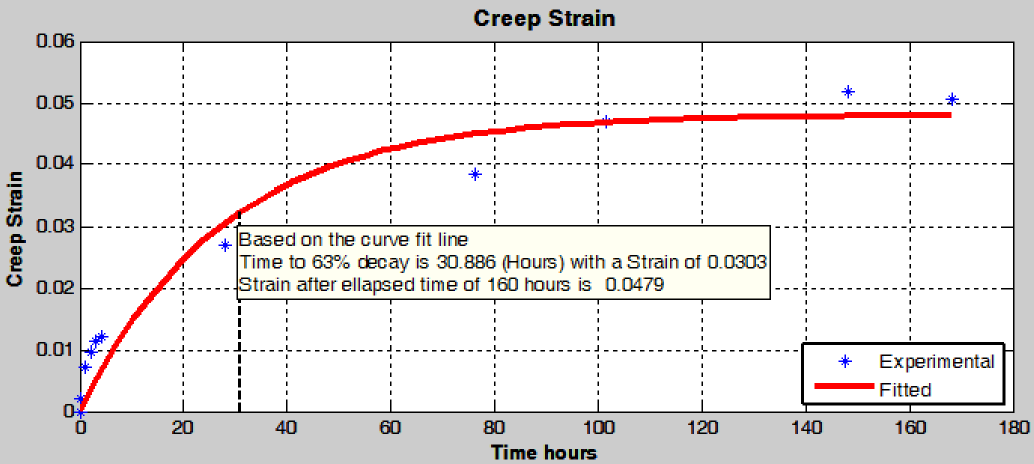
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 1 -> $\varepsilon = a\, \varepsilon_i (1 - e^{-t/\tau})$

Fitted Constants -> a = 11.67 τ = 25.910



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 21.326 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0092

Static Stress σ_i = 1.482 kPa

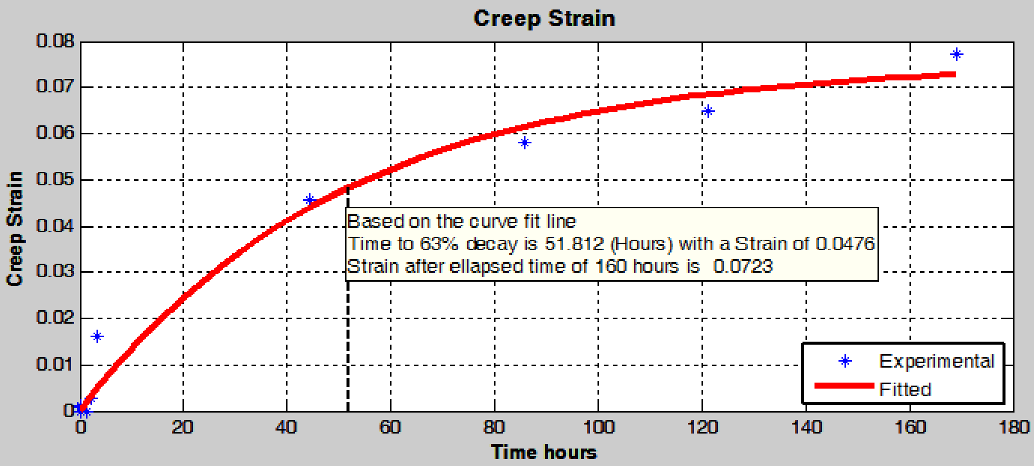
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 5.172 τ = 27.734



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0174

Static Stress σ_i = 1.482 kPa

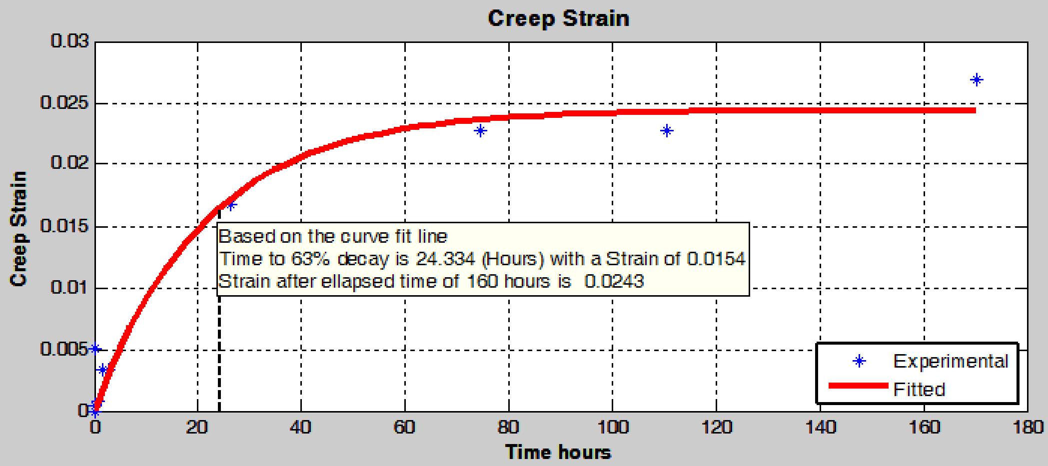
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> a = 4.331 τ = 50.829



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 10.218 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0201

Static Stress σ_i = 1.482 kPa

Temperature = 23 Deg C

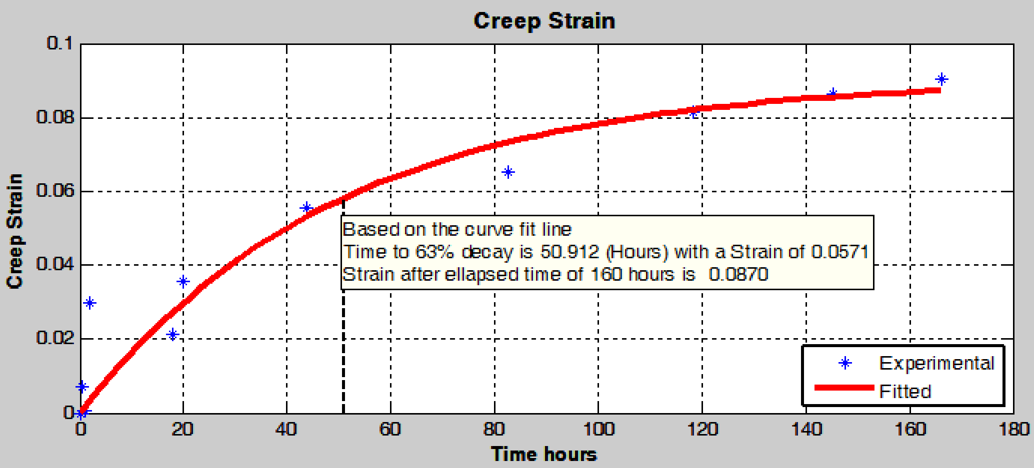
Relative Humidity = 70%

FIT INFORMATION

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Fitted Constants -> $a = 1.209$ $\tau = 21.607$

Function 2



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 14.863 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0134

Static Stress σ_i = 1.482 kPa

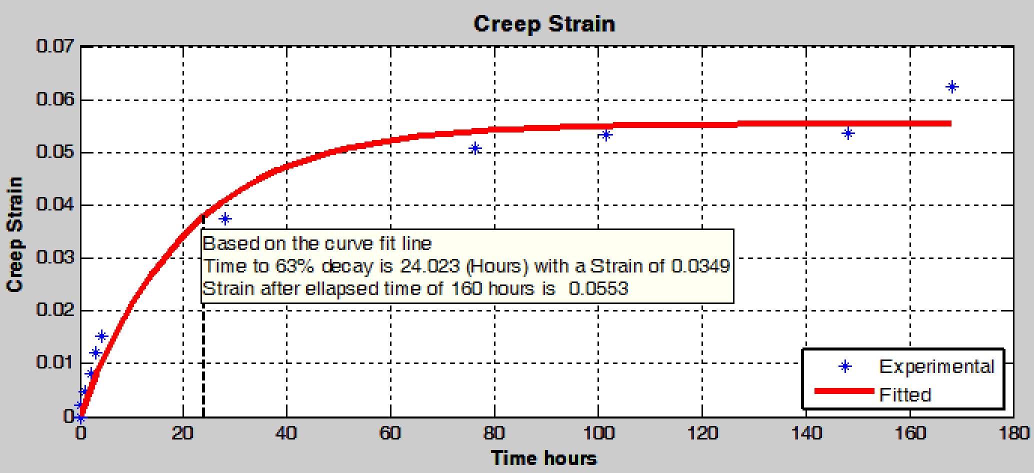
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 0.906 β = 0.020



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 15.822 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0130

Static Stress σ_i = 1.482 kPa

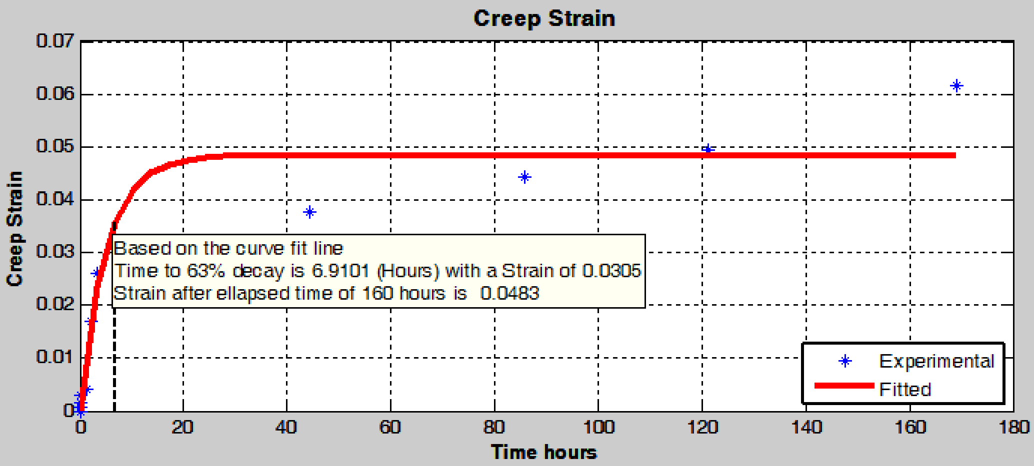
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta t)}]$

Fitted Constants -> a = 0.590 β = 0.048



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0178

Static Stress σ_i = 1.482 kPa

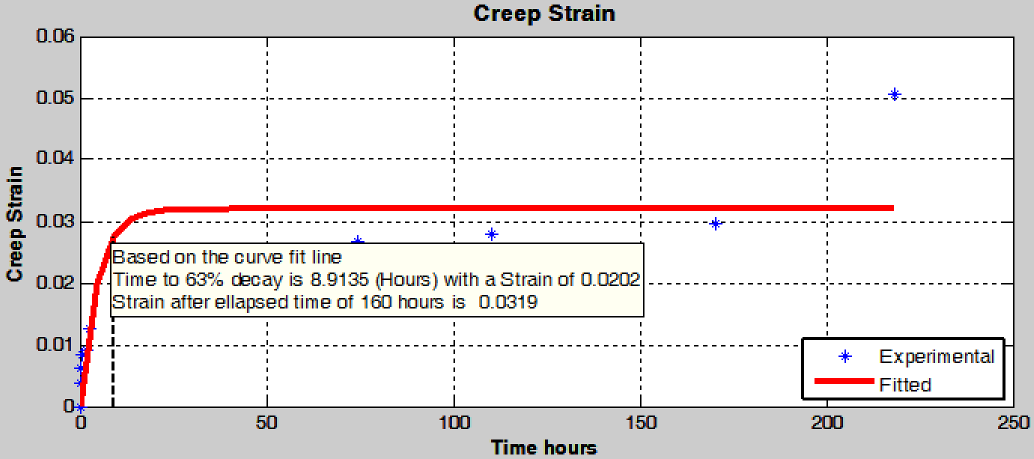
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> $a = 0.371$ $\beta = 0.193$



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 21

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 10.218 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0200

Static Stress σ_i = 1.482 kPa

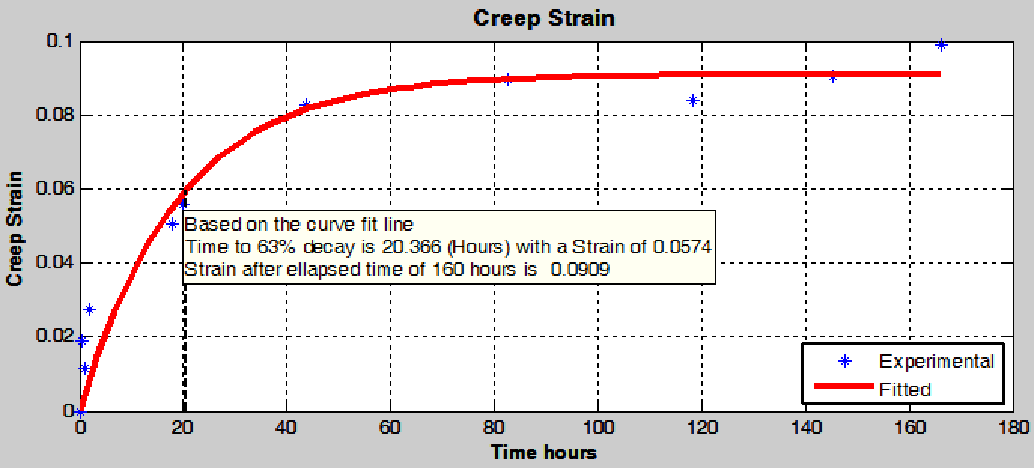
Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 0.220 β = 0.219



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 30.656 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0066

Static Stress σ_i = 1.482 kPa

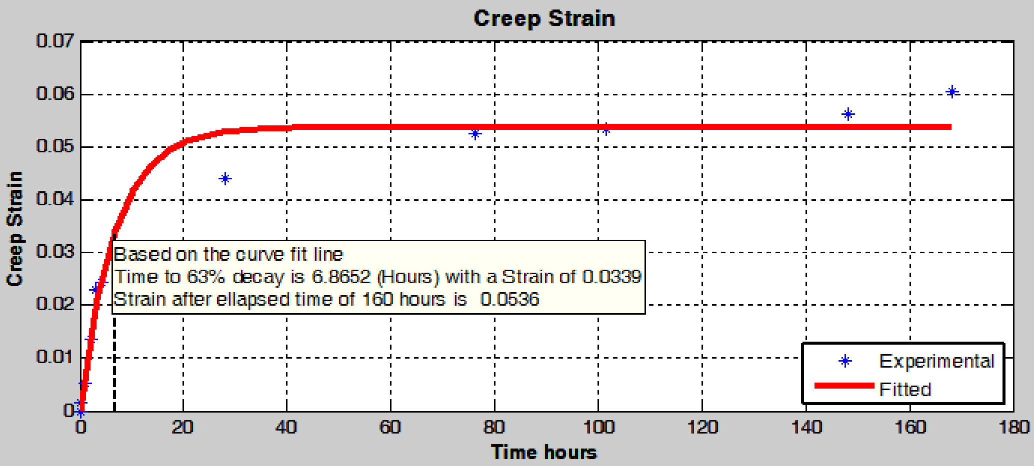
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 1.880 β = 0.051



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 20.437 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0096

Static Stress σ_i = 1.482 kPa

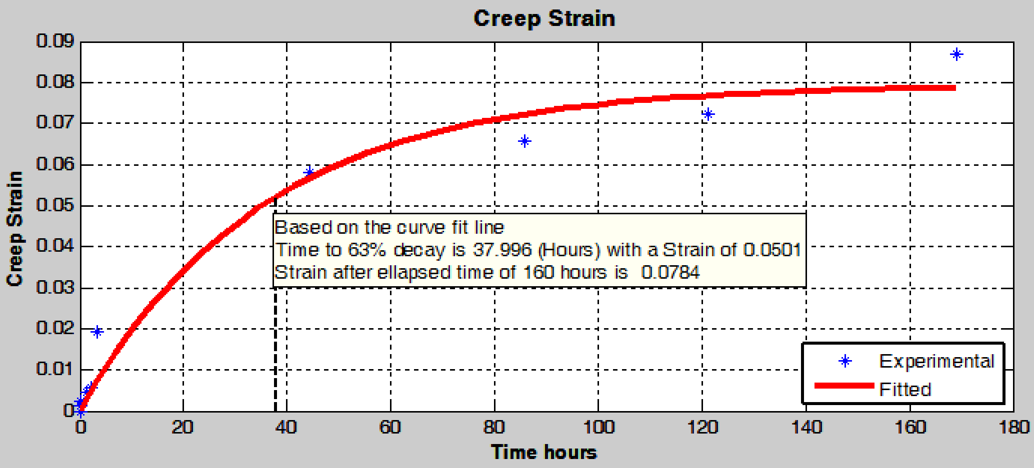
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta t)}]$

Fitted Constants -> a = 0.739 β = 0.146



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0174

Static Stress σ_i = 1.482 kPa

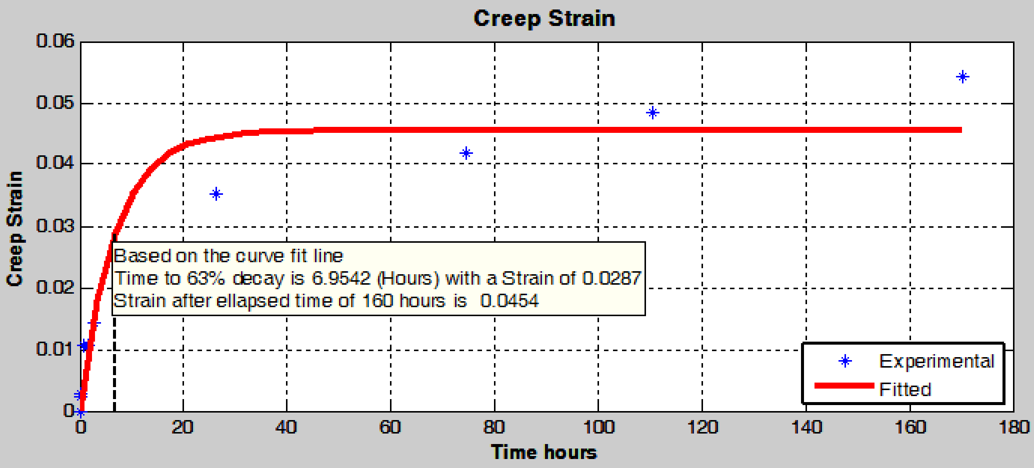
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 2 -> $a\, \sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 0.610 β = 0.028



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 22

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 7.5462 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0263

Static Stress σ_i = 1.482 kPa

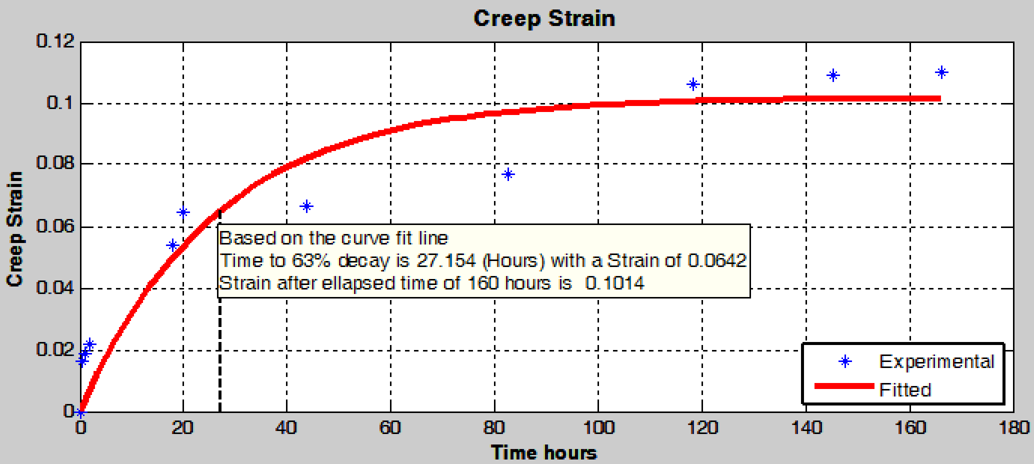
Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 0.231 β = 0.144



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 30%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 23.357 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0086

Static Stress σ_i = 1.482 kPa

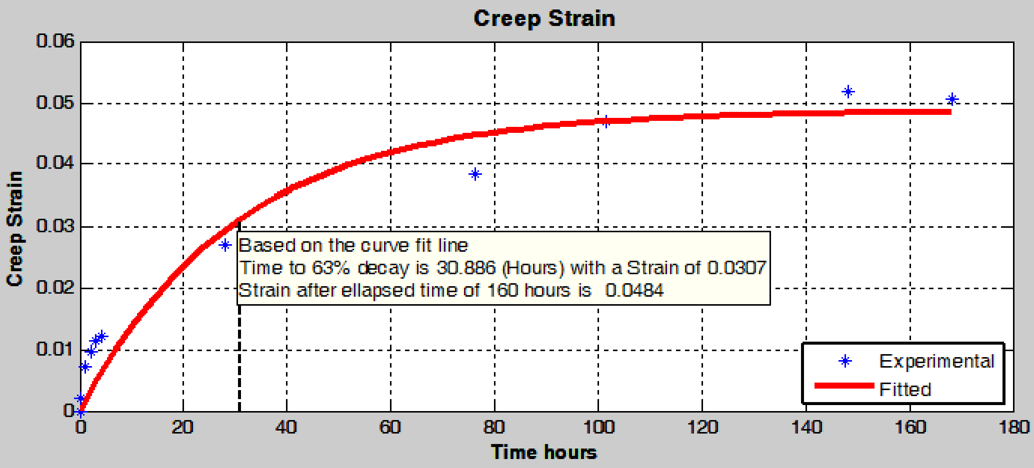
Temperature = 23 Deg C

Relative Humidity = 30%

FIT INFORMATION

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> $a = 1.601$ $\beta = 0.037$



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 50%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 21.326 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0092

Static Stress σ_i = 1.482 kPa

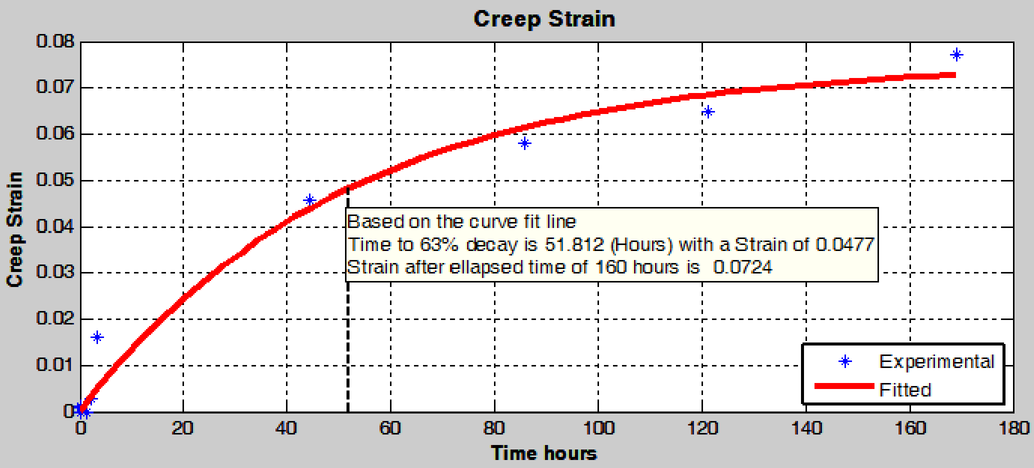
Temperature = 23 Deg C

Relative Humidity = 50%

FIT INFORMATION

Function 2 -> $a\, \sigma_i/k_i[1 - e^{(-\beta t)}]$

Fitted Constants -> $a = 0.700$ $\beta = 0.033$



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 60%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 11.407 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0174

Static Stress σ_i = 1.482 kPa

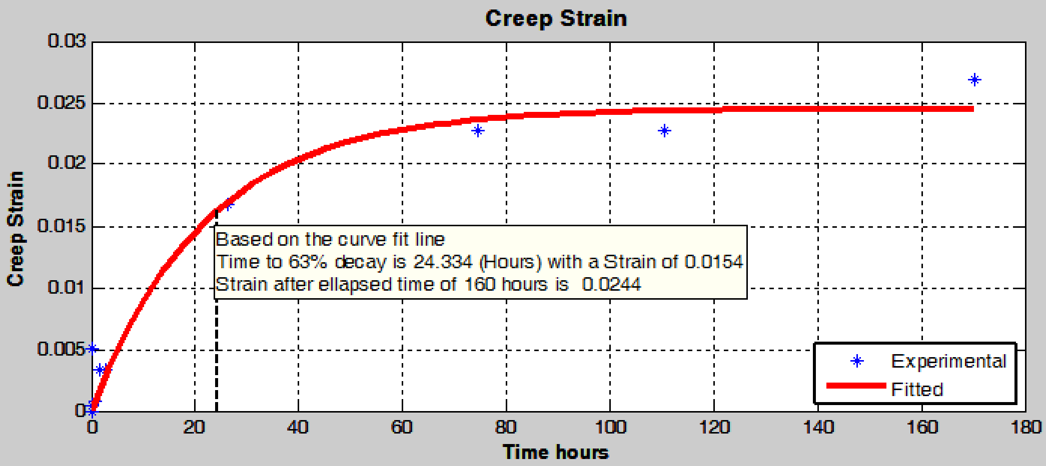
Temperature = 23 Deg C

Relative Humidity = 60%

FIT INFORMATION

Function 2 -> $a\, \sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> $a = 0.581$ $\beta = 0.019$



TEST INFORMATION

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Creep File and Sheet Name - creepTest.xlsx - Sheet 70%

Sample Number - 23

Size - 75 x 75 - 28 Nominal Cushion Height

Material Stiffness k_i = 10.218 kN/m

Static Load = 8.338 N

Static Strain ε_i = 0.0201

Static Stress σ_i = 1.482 kPa

Temperature = 23 Deg C

Relative Humidity = 70%

FIT INFORMATION

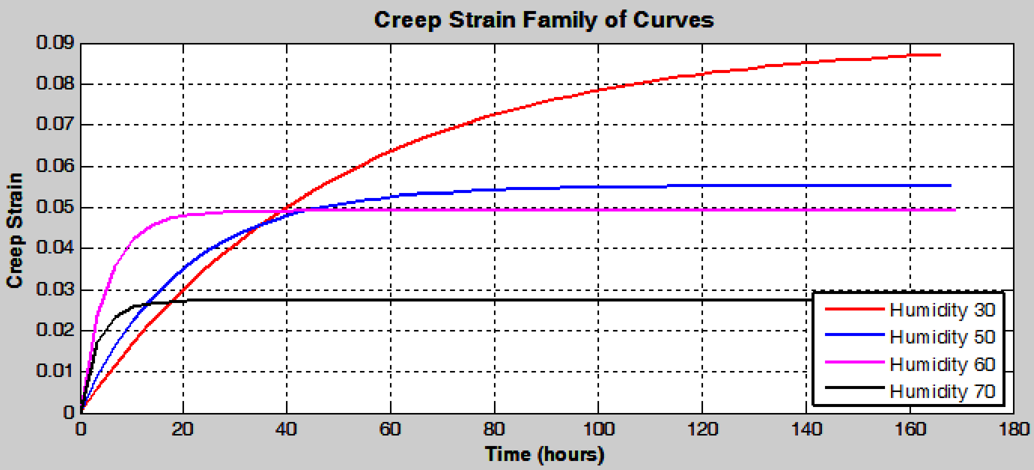
Function 2 -> $a\, \sigma_i/k_i[1 - e^{(-\beta\, t)}]$

Fitted Constants -> a = 0.168 β = 0.044

Appendix C

Family of Curves Based on Fitted Graphs

Function 1



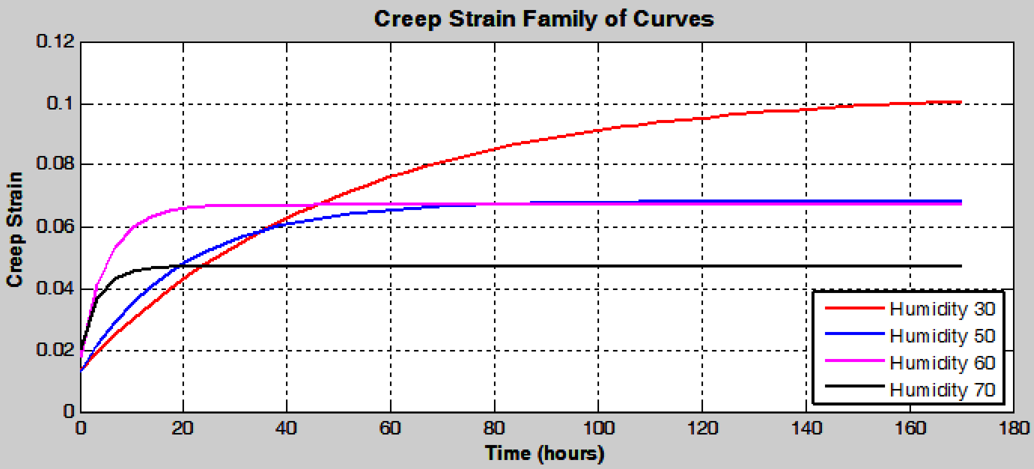
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 21

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Static Strain Not Included



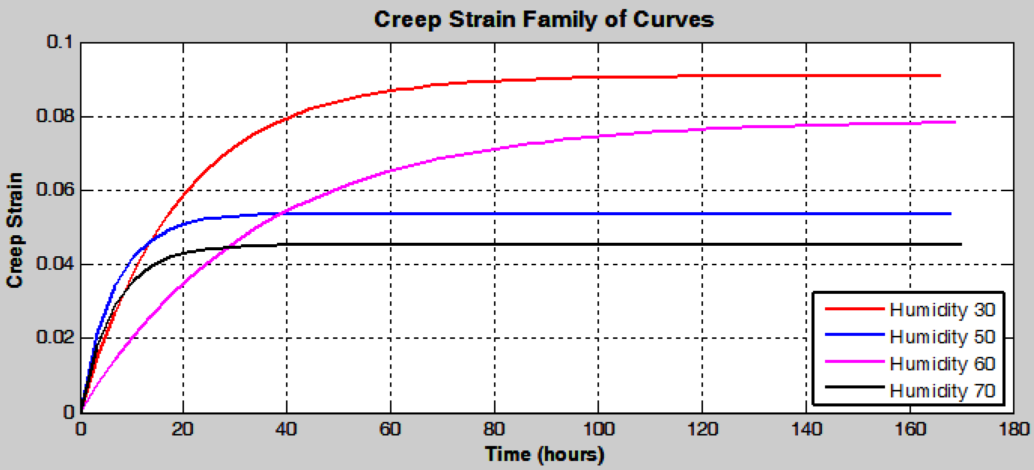
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard

Sample Number - 21

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Static Strain Included



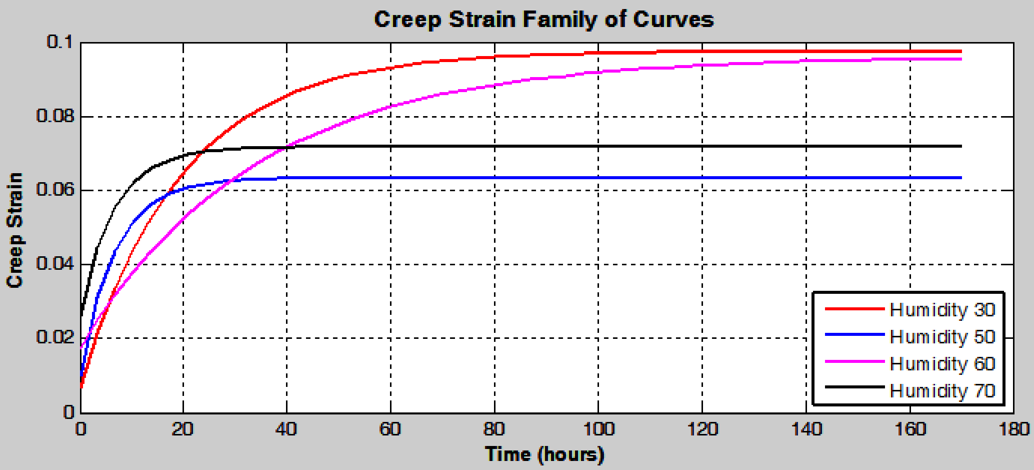
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 22

Function 1 -> $\varepsilon = a\, \varepsilon_i(1\text{-}e^{-t/\tau})$

Static Strain Not Included



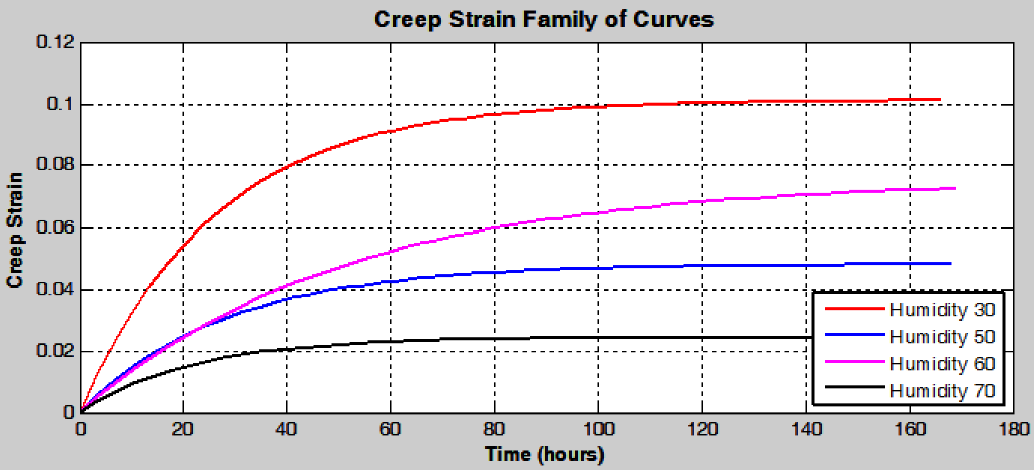
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard

Sample Number - 22

Function 1 -> $\varepsilon = a\,\varepsilon_i(1\text{-}e^{-t/\tau})$

Static Strain Included



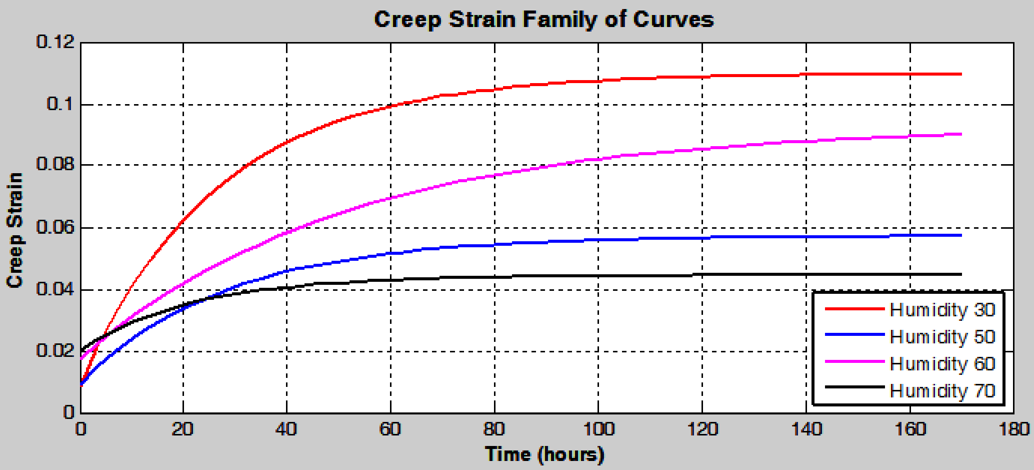
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 23

Function 1 -> $\varepsilon = a\,\varepsilon_i(1\text{-}e^{-t/\tau})$

Static Strain Not Included



CURVE FIT

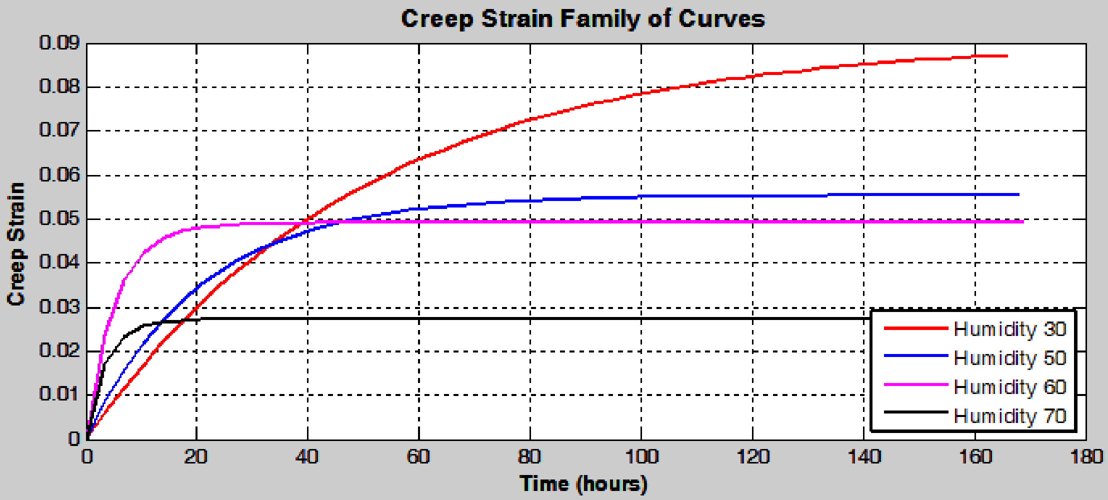
Material -> Multilayered Pre-Compressed Corrugated Fibreboard

Sample Number - 23

Function 1 -> $\varepsilon = a\,\varepsilon_i(1-e^{-t/\tau})$

Static Strain Included

Function 2



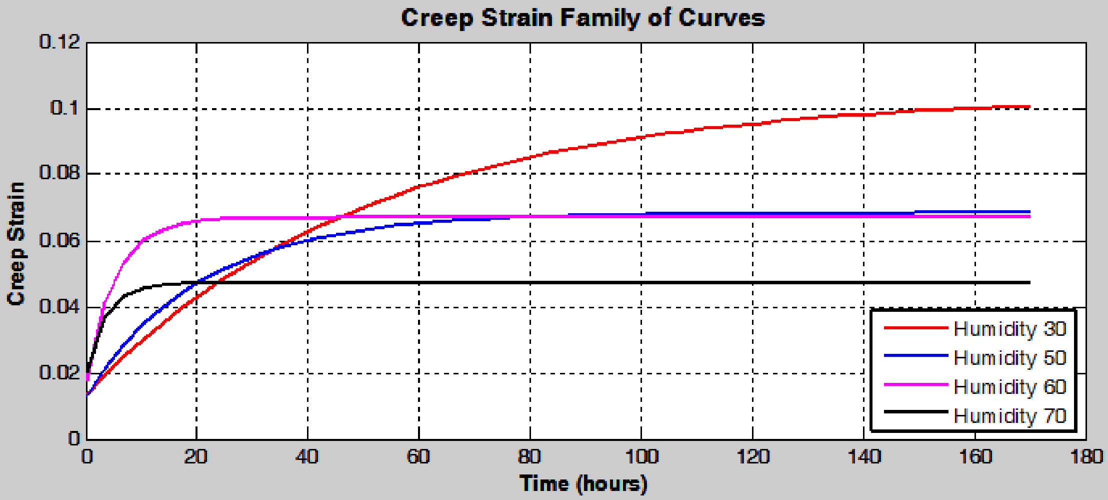
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 21

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}$

Static Strain Not Included



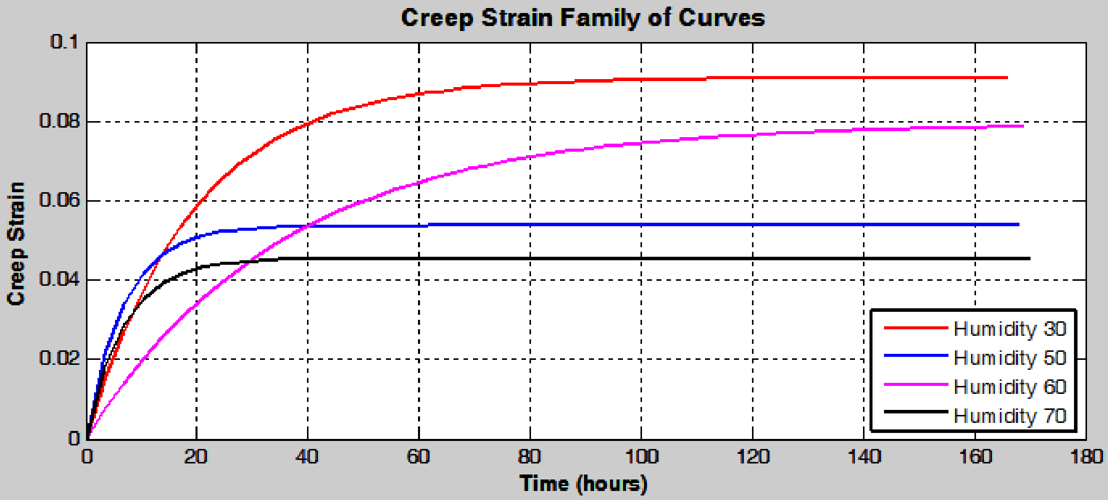
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard

Sample Number - 21

Function 2 -> $a\ \sigma_i/k_i[1 - e^{(-\beta\ t)}$

Static Strain Included



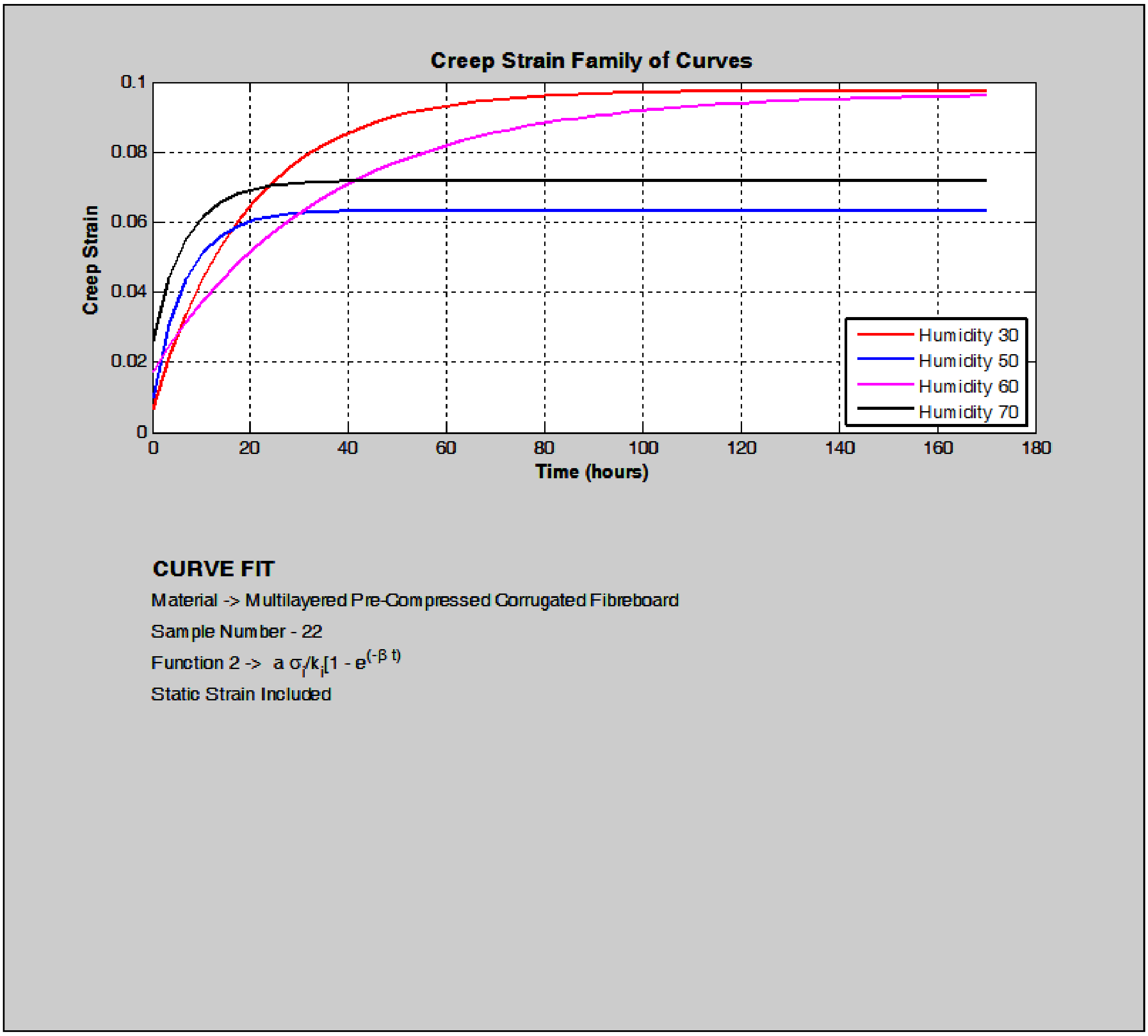
CURVE FIT

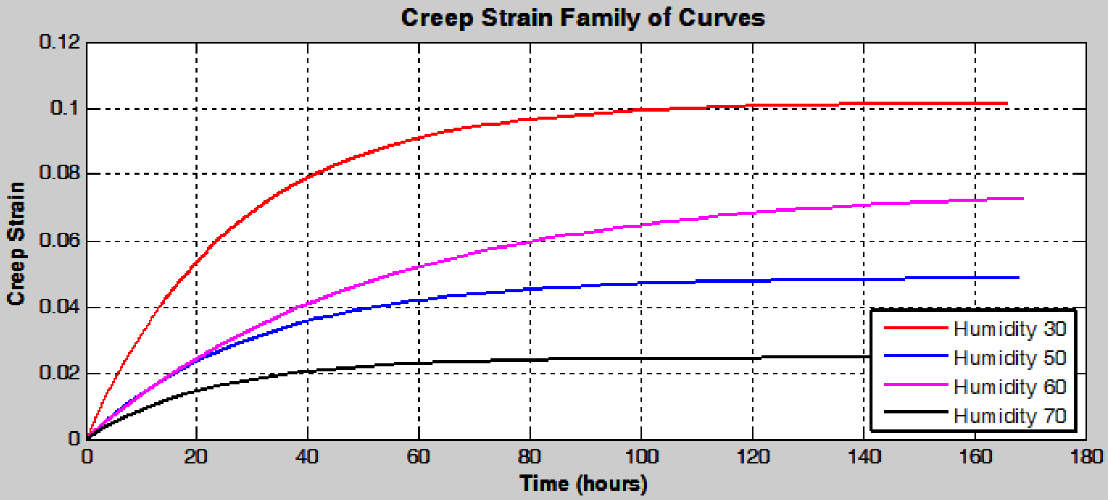
Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 22

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\, t)}$

Static Strain Not Included


Creep Strain Family of Curves
Creep Strain
Time (hours)
0
0.02
0.04
0.06
0.08
0.1
0
20
40
60
80
100
120
140
160
180
Humidity 30
Humidity 50
Humidity 60
Humidity 70
CURVE FIT
Material -> Multilayered Pre-Compressed Corrugated Fibreboard
Sample Number - 22
Function 2 -> a $\sigma_i/k_i[1 - e^{(-\beta t)}$
Static Strain Included



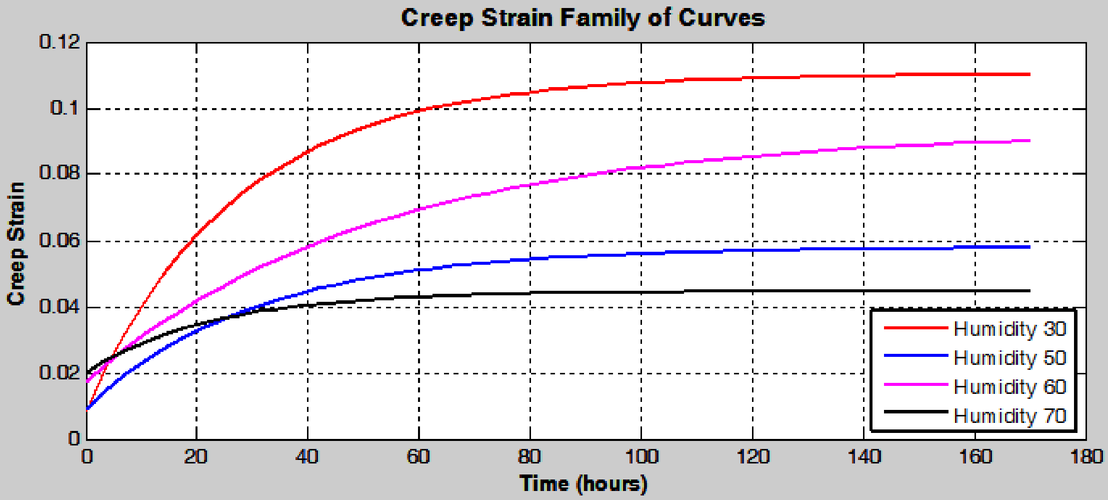
CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard - Type C Flute

Sample Number - 23

Function 2 -> $a\ \sigma_i/k_i[1 - e^{(-\beta\ t)}$

Static Strain Not Included



CURVE FIT

Material -> Multilayered Pre-Compressed Corrugated Fibreboard

Sample Number - 23

Function 2 -> $a\,\sigma_i/k_i[1 - e^{(-\beta\,t)}$

Static Strain Included