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## Prediction of Compressive Creep Behaviour in Flexible Polyurethane Foam Over Long Time Scales and at Elevated Temperatures

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## Test method

## Prediction of compressive creep behaviour in flexible polyurethane foam over long time scales and at elevated temperatures

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## ABSTRACT

Compressive creep gradually affects the structural performance of flexible polymeric foam material over extended time periods. When designing components, it is often difficult to account for long-term creep, as accurate creep data over long time periods or at high temperatures is often unavailable. This is mainly due to the lengthy testing times and/or inadequate high temperature testing facilities. This issue can be resolved by conducting a range of short-term creep tests and applying accurate prediction methods to the results. Short-term creep testing was conducted on viscoelastic polyurethane foam, a material commonly used in seating and bedding systems. Tests were conducted over a range of temperatures, providing the necessary results to allow for the generation of predictions of long-term creep behaviour using time-temperature superposition. Additional predictions were generated, using the William Landel Ferry time-temperature empirical relations, for material performance at temperatures above and below the reference temperature range. Further tests validated the results generated from these theoretical predictions.

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## 1. Introduction

A viscoelastic material is one which exhibits behaviour which is characteristic of both solids and liquids [1]. Polymeric materials are known to exhibit viscoelastic behaviour, which is dependent on the time scale of the loading and/or the temperature of the material [2]. Two common phenomena in materials which are due to viscoelasticity are creep and stress relaxation [3] - increasing strain over time at constant load and diminution of reaction force at constant strain respectively [3].

Understanding long-term creep behaviour can have important implications for the design and manufacture of components made from cellular viscoelastic foam

materials. One application, which is of particular interest to the medical industry, is the design of wheelchair seating systems for users with limited mobility who may not be able to shift bodyweight unaided. The foam's viscoelasticity is enhanced with the application of body heat. This leads to increased envelopment, which results in greater surface contact area between the body and supporting cushion, resulting in lower pressures at the seat/body interface [4,5].

Conventional polyurethane foam is an open celled elastomeric polymer whose constituent elastomer (polyurethane rubber) can undergo large and reversible elastic deformations. Elastomeric foams exhibit several regions of different stress-strain behaviour in uniaxial compression: (i) approximately linear behaviour for strains less than about 0.05 - this linear elasticity arises from the bending of the cell edges, (ii) a plateau region in which strain increases at constant or nearly constant stress up until a strain of roughly 0.6 - this plateau arises from elastic buckling of the

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cell edges and (iii) a densification of the collapsed cell edges causing the foam to behave in a similar manner to its elastomeric constituent material. In this final region, the slope of the stress-strain curve increases exponentially with strain as the crushed foam's cell struts and vertices come into contact [6]. The large strain response of flexible polyurethane foam cannot be accurately described by linear-elastic models. Its non-linear elastic response is classified as hyperelastic. The mechanical behaviour of these hyperelastic polymers is dependent on a number of variables, including: the material properties of the constituent polymer; time effects; climatic (temperature and humidity) effects and strain rate effects. Microstructural inhomogeneity is also prevalent within this type of polymer. This is mainly due to inconsistencies within the foam manufacturing process. Material hyperelasticity combined with the structural inhomogeneity of the material mean that the material exhibits complex loading behaviour which can be difficult to understand and model.

Viscoelastic polyurethane foam, commonly referred to as memory foam, is manufactured to exhibit augmented viscoelastic effects when compared with conventional polyurethane foam. In addition to the complexities of the material's loading behaviour, in any accurate polymeric material design analyses viscoelastic behaviour must also be accounted for. Many authors have conducted analysis of the hyperelastic behaviour of flexible foam material for a range of different applications, using existing material models or developing their own novel equations. Research by Mills et al. used Ogden's material model [7] to analyse the hyperelastic behaviour of personal protection equipment (running shoe soles and crash helmets) [8–10]. Gruijic et al. [11] and Silber et al. [12,13] also used Ogden's model to represent foam in auto seat passenger models. Zhang et al. [14] and Liu and Subhash [15] have developed constitutive equations capable of modelling hyperelastic foam behaviour. Attempts at simultaneously modelling hyperelastic and viscoelastic behaviour are not as common. The authors combined Ogden's model with a set of Prony Series constants, generated from stress relaxation data, to model viscoelasticity [16]. Creep is the predominant viscoelastic phenomenon in seating applications or indeed any application where an approximately constant load is applied over extended time periods. For this reason, it was decided to use creep data to generate predictions of long term viscoelastic behaviour in this work.

Short-term creep test data was used with the Time-Temperature Superposition (TTS) principle to generate long-term master-curve predictions of viscoelastic polyurethane foam creep compression behaviour. Creep compression master-curves are then used in conjunction with the time-temperature relationship delineated by Williams, Landel and Ferry [17] to generate creep predictions beyond the time or temperature range of testing. Predictions are generated over long time periods at a temperature below the range of original testing and over short time periods at temperatures above the original temperature range. The longer time scale and higher temperature of the predictions were chosen to represent extreme test-cases which may not be achievable in a typical laboratory setting. Creep compression curve forecasts are

validated by comparison with physical test results. The prediction methodology presented here may be applied to a wide range of polymers and polymeric foams with many different applications in industries such as the aerospace, transport, medical device and packaging industries.

## 2. Time-temperature superposition and Williams, Landel and Ferry theory

### 2.1. Time-temperature superposition principle

Studies involving the compressive creep behaviour of polymers should be carried out over long time periods at the expected service (often ambient) temperatures and stress levels. However, for many reasons, including the time required to conduct long-term tests, this is generally not possible. Two accelerated test methods exist, one using the Time-Temperature Superposition (TTS) principle and the other using the Time-Stress superposition (TSS) principle, which are utilised to generate predictions of long-term creep behaviour. TTS relies on the fact that higher temperatures accelerate viscoelastic phenomena within viscoelastic materials, while the basis for TSS is that higher stresses accelerate viscoelastic phenomenon. Some authors have used TTS, independently proposed by Leaderman, Tobolsky and Andrews [18–20], to study viscoelastic creep and viscoelastic stress relaxation in rigid polymers [21–25]. The TTS method was applied, in this study, to the characterisation of the long-term behaviour of viscoelastic polyurethane foam. Other researchers have used TSS to obtain long-term data from short term creep tests with different applied stresses [26–28].

In this work, creep compression test results were compiled from tests conducted under identical creep stresses over a range of temperatures. The array of creep curves obtained from these tests were shifted along the time-scale, each by a different factor which corresponded to an individual testing temperature, such that they converged to form an extended creep curve at the reference temperature. This extended curve is referred to as the master-curve and it should represent the actual creep behaviour at the reference temperature. TTS is only plausible for thermorheologically simple materials, meaning that all relaxation times and retardation times are assumed to have the same temperature dependence. The shift factor,  $a_T$ , at any temperature is the ratio between the time for a viscoelastic creep process,  $\lambda_i$  to proceed at the test temperature,  $T$ , and the time for the same process to proceed at a reference temperature,  $T_r$ , as given in Eq. (1).

$$\lambda_i(T) = a_T \lambda_i(T_r) \quad (1)$$

### 2.2. WLF equation

Williams, Landel and Ferry [17] developed an empirical formula (Eq. (2)) describing the time-temperature relationship through the shift factor,  $a_T$ :

$$\log a_T = \frac{-c_1(T - T_r)}{(c_2 + T - T_r)} \quad (2)$$

where  $c_1$  and  $c_2$  are material dependent parameters which are a function of material type and reference temperature,  $T_r$ , and  $T$  represents test temperature.

An important parameter for polymers is the glass transition temperature ( $T_g$ ), which characterises the transition from the solid to the rubber (or foam) or viscous liquid. For the type of flexible polyurethane foam used in this study, the glass transition temperature is between 5 and 25 °C [29,30]. Below  $T_g$  the configurations of polymer chain backbones are largely immobilised and the large changes in viscoelastic behaviour associated with time and temperature differences do not appear [1]. The glass transition temperature for polyurethane foam materials varies widely, largely depending on the cross-linking density and the molecular weight of the foam [30]. Above  $T_g$ , the polymer is viscoelastic or elastomeric and can sustain large, often recoverable, deformations without true yield or fracture, providing a flexible foam.

Eq. (2) does not hold below  $T_g$  as it predicts a monotonic increase of  $\log a_T$  with decreasing temperature, implying that the inflection point which exists near  $T_g$  is not accounted for. The empirical formula is expected to be accurate for this material within the temperature range  $T_g$  to  $T_g + 100$  °C [17].

### 3. Test methods

Creep compression testing was conducted on the open-celled viscoelastic polyurethane foam commercially known as Sunmate, manufactured by Dynamic Systems Inc., which had a density of 85 kg/m<sup>3</sup>. Standard test procedures were used to conduct all creep compression testing [31].

#### 3.1. Apparatus

A test rig capable of measuring creep compression at elevated temperatures was constructed for this work, see Fig. 1.

The creep test apparatus was constructed entirely from the same mild steel material. Identical and equidistant holes were drilled at the corners of the top two flat plates. These plates were then bolted together and separated by

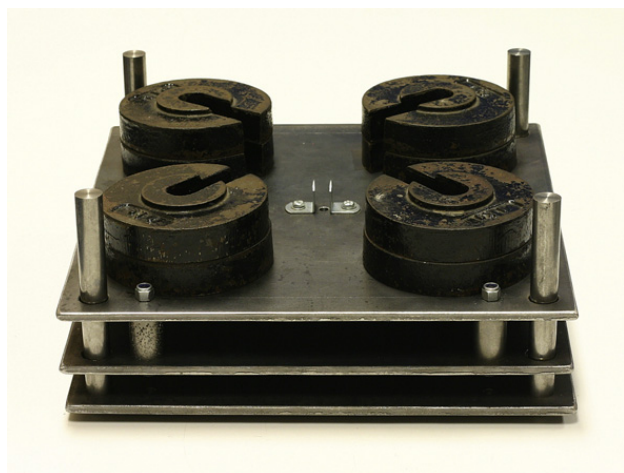


Fig. 1. Creep compression testing apparatus, additional weight applied.

30 mm spacers. Four vertical bars were bolted to the four corners of the base plate. The top plates slid freely up and down the four vertical bars, compressing the sample in between. Additional weights were placed onto the top plate to provide an initial strain value of approximately 0.5 which was relevant to the seating application.

Two angled brackets were attached to the top plate; the bottom of a Variomh linear potentiometer was connected to these brackets via a small cylindrical bar (see Fig. 2). All displacement readings were taken using this potentiometer which had a stroke of 100 mm, an accurate reading range of  $\pm 0.01$  mm and a maximum operating temperature of 175 °C. The potentiometer was powered using a 5 V power supply, all voltage readings in the range of 0 – 5 V were linearly proportional to a mechanical stroke in the range 0 – 100 mm. Potentiometer readings were recorded with a digital input National Instruments (NI) 9205 module connected to a NI cRIO-9073 DAQ unit.

The apparatus was placed inside a temperature chamber (Fig. 2). The top of the potentiometer was connected to an external steel bar, which was in turn held vertically in place using two aluminium blocks. A hole in the top of the temperature oven allowed the bottom of the potentiometer to feed through into the oven and be connected to the top plate. All thermal measurements were taken from within the centre of the sample, measured with a T-type thermocouple and recorded using a NI-9211 module connected to the same NI cRIO-9073 DAQ unit. Temperature measurements were recorded throughout the period of each test.

#### 3.2. Creep testing apparatus calibration

Comparative creep tests were conducted using the creep test apparatus and a Lloyds LR30k material test machine with a calibrated 2.5 kN load cell. Creep compression tests were conducted on test samples at room temperature of 23 °C  $\pm$  2 °C. The results of the comparison tests are presented below in Fig. 3. The discrepancy noted at the beginning of the tests can be attributed to different loading rates. The sample in the custom test rig creep test was loaded faster which resulted in a slightly higher strain in the very early stages (<50 s) when compared to the Lloyds test rig creep test. This had little effect on long-term viscoelastic material behaviour, which corresponds to previous findings on polymer materials [25]. The response during the loading period of the test procedures was ignored and only the data obtained during the period of constant displacement or constant load were used to determine material properties [32,33]. The two curves matched each other over the remainder of the 20 min test, after the initial loading period. After 100 s, a difference of 1.6% was noted, which reduced to 0.5% after 200 s. The similarities of the two curves demonstrate that the creep test apparatus was capable of providing results with the required accuracy.

#### 3.3. Creep testing procedures

Identical samples, 50 mm in height and 125 mm in length and width, were prepared from the same batch of

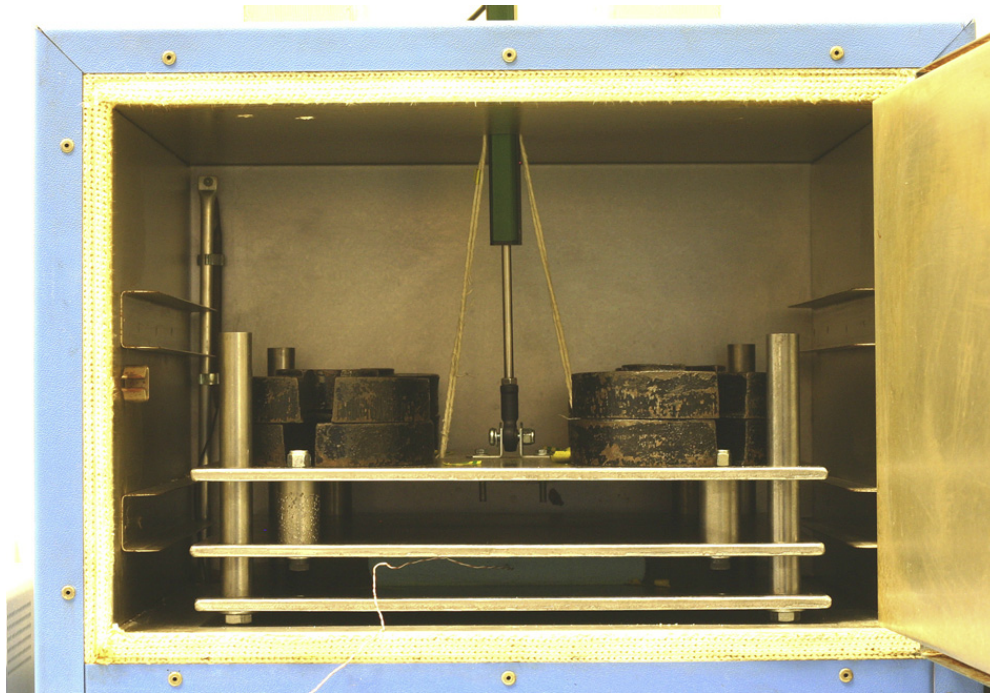


Fig. 2. Creep compression apparatus inside temperature chamber.

material. Prior to testing, each sample was mechanically conditioned with a cycling procedure of four cycles to a strain of 0.8 to remove any virgin foam effects such as the Mullins effect [34]. The modulus over the course of the fourth cycle was monitored and there was a maximum variance of 6% between all samples. Each mechanically conditioned sample was then positioned centrally on the base plate of the creep compression apparatus. The compression plate was held at sample height distance from the bottom plate using two identical spacing blocks. Weights were then placed on the upper compression plate of the test apparatus. The combined weight of the compression plates and the additional weights was 20.6 kg. The apparatus, with sample in place, was placed into the

test chamber and thermally conditioned, unstrained, at test temperature for twelve hours prior to testing. This time was allowed to ensure that the complete system was at uniform temperature. Tests were conducted at six predetermined temperatures: 30, 45, 60, 70, 83 and 115 °C. The tests at the highest and lowest temperatures were used for prediction validation purposes; the results of the other tests were used to generate these predictions. All the tests were conducted over a 20 h period except the 30 °C test, which lasted 35 days. To begin a test, the spacing blocks were removed and the load was applied to the test sample.

#### 4. Results and discussion

##### 4.1. Creep test results

The results of tests conducted at 45, 60, 70 and 83 °C were plotted in normalised creep strain format in Fig. 4. It is assumed here that the loading period takes 100 s to complete and so creep was, therefore, measured from this point [32,33]. Normalised creep strain,  $\epsilon_n(t)$ , is defined in Eq. (3) as:

$$\epsilon_n(t) = \frac{\epsilon(t)}{\epsilon_{100}} \quad (3)$$

where  $\epsilon(t)$  is the creep strain and  $\epsilon_{100}$  is the creep strain after 100 s.

There is obvious temperature dependence, with creep strain increasing as test temperatures increases. The proximity of the test temperature to the glass transition temperature is the dominant factor influencing creep strain. It is noted in Fig. 4 that the creep compression curves at the higher temperatures, 70 and 83 °C, display

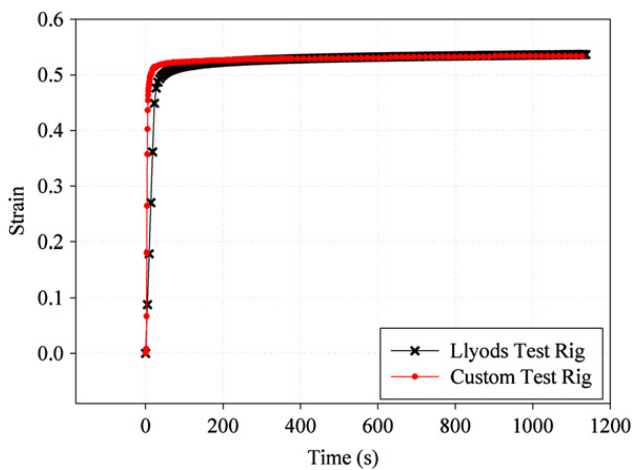


Fig. 3. Comparison of creep tests conducted on current creep testing set-up and Lloyds testing machine.

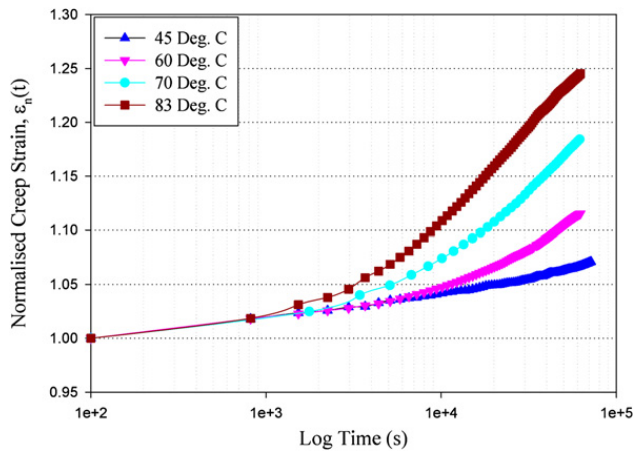


Fig. 4. Plot of normalised creep strain for viscoelastic polyurethane foam over log time at four different temperatures.

a significant acceleration in creep strain over the period of the test. Increased temperatures are known to cause hydrogen bond disruption which increases the amount of chain slippage. It is assumed that this chemical behaviour is the primary reason for the accelerated creep rate at these higher temperatures [35]. This acceleration in viscoelastic effects around 70 °C has previously been noted by one of the authors [25], dynamic and static testing procedures having been conducted on a range of different polymeric materials to substantiate this finding.

#### 4.2. Master-curve creation

The creep curves (Fig. 4) obtained from the tests at 60, 74 and 83 °C were shifted back into the creep curve at the 45 °C reference temperature. The time-scale of each of the four curves was multiplied by a temperature dependent factor,  $a_T$ , moving each curve horizontally along the time-scale towards the reference temperature. This extended curve, displayed in Fig. 5, is referred to as the master-curve and it should represent this material's actual creep behaviour at the reference temperature. The master-curve is constructed by using sections from each of the four input creep curves (see Fig. 5) where each section is signified by a different symbol. The shift factors for this material at this reference temperature are displayed in Table 1. This use of TTS to generate a master-curve provided creep predictions for up to 23.2 days, at the reference temperature, from test data generated in 3.2 days.

#### 4.3. Application of WLF theory

The WLF equation (Eq. (2)) was curve fitted to the log  $a_T$  values (Table 1) to enable predictions for the behaviour at temperatures beyond the scope of testing. Parameters  $c_1$  and  $c_2$  were calculated using a least squares optimisation procedure as  $-5.01$  and  $-94.06$  respectively. An accurate curve fit was obtained, see Fig. 6.

##### 4.3.1. Long-term prediction at low temperature

Extrapolation of the WLF equation to a value of 30 °C, using the calculated constants, revealed a log  $a_T$  value of

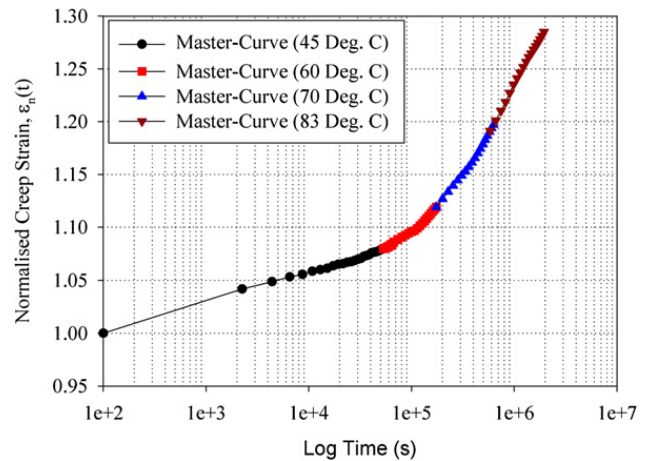


Fig. 5. Viscoelastic polyurethane foam creep master-curve.

$-0.95$  (Fig. 6). This gave a WLF shift factor,  $a_T$ , of 8.94. This shift factor was applied to the time-scale of the creep master-curve and the resulting shifted WLF master-curve gave an approximation for the creep strain behaviour at 30 °C. Use of the WLF theory in conjunction with Master-curve theory can provide predictions for behaviour 208 days into the future from 3.2 days of testing, thus potentially reducing testing time-scales by a factor of 65. The creep strain from an actual test carried out at 30 °C was then compared with the 30 °C creep strain WLF master-curve and the 40 °C original master-curve (Fig. 7(a)). The 30 °C test results and WLF predictions correspond well at longer time-scales (Fig. 7(b)), with some initial inaccuracies in the early periods of testing. The characteristic creep behaviour takes about 2% of the total predicted time to manifest itself, meaning that predictions at lower time periods (<2% of total predicted test time) should be disregarded. The prediction generated here using the TTS master-curve and WLF method provides a good estimate of long-term creep behaviour, which is not always achievable due to the long time periods required. A creep compression test has been conducted for validation purposes over a longer time period of 35 days at 30 °C. The predictions generated here have been proven to be accurate up to a 35 day time period, see Fig. 7(a) and (b).

##### 4.3.2. Short-term prediction at high temperature

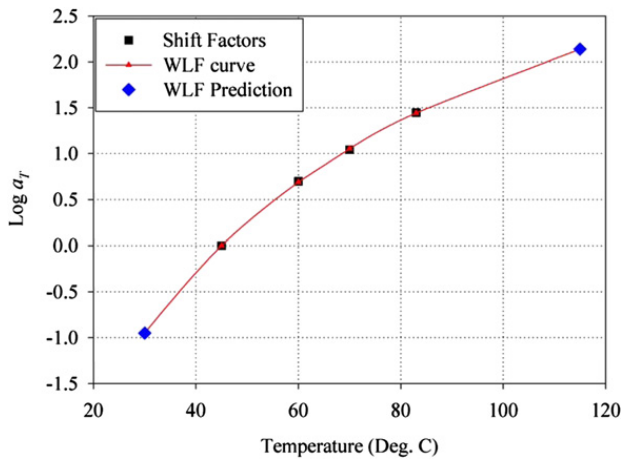
The WLF prediction at a temperature of 115 °C is presented in Fig. 8(a) and (b). A WLF shift factor of  $7.24 \times 10^{-3}$  was generated from a log  $a_T$  value of 2.139 from the WLF curve in Fig. 6. This factor was then applied to the time-scale of the creep master-curve, generating the WLF prediction for creep in compression at 115 °C. A creep compression validation test was also conducted at 115 °C. Fig. 8(a) displays the creep compression predictions, at

Table 1

Log shift factors generated from the creation of master-curve at reference temperature of 45 °C.

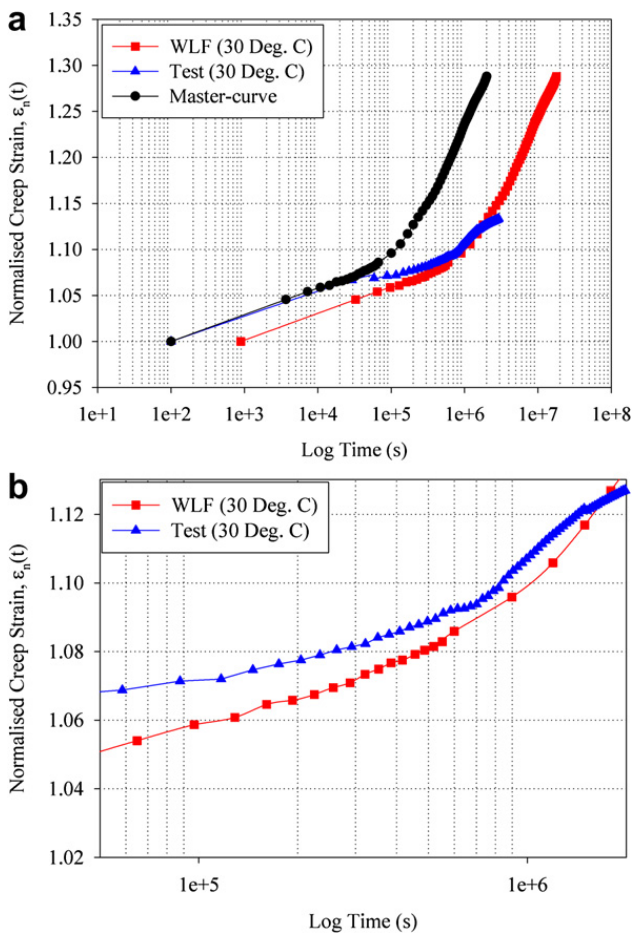
Temperature (°C)	45	60	70	83
$a_T$	1	5	11	28
Log $a_T$	0	0.69897	1.0413927	1.447158



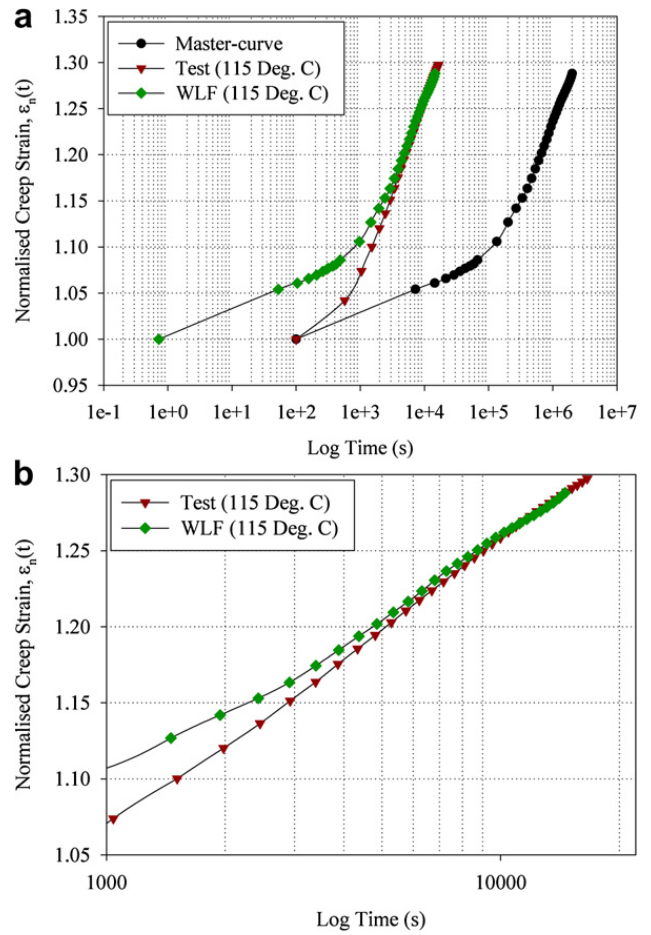


**Fig. 6.** Master-curve log shift factors compared with WLF curve-fit. WLF curve extrapolated to enable predictions of material behaviour at 30 °C and 115 °C.

a temperature more than 30 °C higher than the highest temperature input creep curve, presented along with the original master-curve and the results of the validation test. It was noted again that the characteristic creep behaviour takes a certain amount of time to make itself apparent, meaning that predictions at lower time periods (<2% of



**Fig. 7.** (a): Reference Master-curve (45 °C), predicted WLF master-curve (30 °C) and actual creep test data (30 °C). (b): Expanded view of the predicted WLF master-curve (30 °C) and actual creep test data (30 °C) in the accurate validated range of the prediction.



**Fig. 8.** (a): Reference master-curve (45 Deg. C), predicted WLF master-curve (115 °C) and physical test curve (115 °C). (b): Expanded view of the predicted WLF master-curve (30 °C) and actual creep test data (30 °C) in the validated range of the prediction.

total predicted test time) should be disregarded. Higher temperature predictions match physical test results well and it is noted the accuracy of prediction improves as the test progresses, see Fig. 8(b). The higher temperature prediction provided using the TTS master-curve and WLF method is extremely useful where test equipment cannot cater for high temperature testing.

### 5. Conclusions

This paper has described a method for forecasting both long-term compressive creep behaviour and high temperature compressive creep behaviour. Creep compression tests were conducted over a range of temperatures on viscoelastic polyurethane foam using a purpose built test rig. Results were found to be strongly temperature dependent, as creep acceleration corresponded to higher temperatures. Time Temperature Superposition (TTS) theory was applied to these test results to generate an extended creep compression curve at a reference temperature of 45 °C. Williams, Landel and Ferry (WLF) empirically generated predictions for creep behaviour below the temperature range of testing were then created, which provided predictions as far as 208 days, with 35 days of this prediction validated. A WLF forecast were also produced at

a temperature 35 °C higher than the initial creep compression tests, with accuracy validated over the extent of this test. The procedure presented here enables accurate prediction of creep compressive behaviour for temperatures or time-scales which are not easily achievable in the laboratory. Future work will include implementation of a validated numerical model, using long term creep data, in a seating design simulation which will include the modelling of temperature dependence.

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