DEVELOPMENT OF CURE KINETICS MODEL, VISCOSITY MODEL AND FIBER BED COMPACTION CURVE FOR CYCOM® EP2750

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ABSTRACT

The aim of this work is to bring new insights into the rheological, thermal-chemical, and compaction properties of the 2 x 2 twill weave CYCOM® EP2750 by Syensqo, to optimize the manufacturing of the composite parts using Syensqo's Double Diaphragm Forming (DDF) process. The cure kinetics of fresh and room temperature aged material was studied using differential scanning calorimetry analysis. The rheological behavior of fresh and aged material was also characterized using oscillatory rheometer with parallel plates. The compaction behavior of the fresh prepreg was studied using a stress relaxation method with a benchmark developed in-house. The cure kinetics of fresh and aged prepreg were described by iso-conversional model. The dependency between the glass transition temperature and its degree of cure was described using DiBenedetto model. A chemo-rheological model, based on Williams-Landel-Ferry model, was adopted to describe the viscosity as a function of temperature and degree of cure. The fiber bed compaction curve of the prepreg was obtained, and it can be adequately described by Gutowski's model. Good agreement was obtained for both cure and viscosity models between the predicted and experimental results, using a typical curing cycle.

Keywords: Carbon fiber prepreg, cure and viscosity modeling, fiber bed compaction

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1. INTRODUCTION

Advanced Air Mobility (AAM) is becoming a captivating and increasingly prominent conversation within the aeronautical domain. AAM designates new means of transporting people and goods in urban and rural areas such as air taxis, drones, remotely piloted aircraft system (RPAS), etc. Unlike traditional aeronautical industry, AAM industry faces a major challenge to achieve high production rates of composite parts with a competitive cost and good material integrity. In this context, Syensqo developed a new fast-curing aerospace grade epoxy prepreg: CYCOM® EP2750.

Little work has been done on the material characterization of CYCOM® EP2750 in the literature [1,2]. The goal of this work is to bring new insights into the thermal-chemical properties, rheological properties, and compaction behavior of 2 x 2 twill weave CYCOM® EP2750.

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This new rapid curing system is intended for out-of-autoclave processes such as compression molding and double diaphragm forming (DDF) and alike, allowing parts to be manufactured much faster than with a conventional autoclave process, while ensuring similar part quality [3]. Since CYCOM® EP2750 is a new material system, there is still a need to further study the in-process material behavior and capture it through models. Accordingly, adaptative manufacturing could help manufacturers to maximize process yield by adjusting specific processing parameters in real time based on real material history.

Therefore, this work focuses on the material characterization of the EP2750 system as a function of the ageing time at room temperature, and the development of material models, which are the fundamental building blocks for adaptive manufacturing. In future works, these models will be integrated into a user-friendly software, linking the material properties in real time to the manufacturing process parameters, which will help the workshop press operators to particularize the process parameters based on the current material pedigree to be molded, thus reducing the part rejection rate.

1.1 Overview of contents

The cure kinetics of fresh and room-temperature aged CYCOM® EP2750 prepreg was studied. The evolution of glass transition temperature, reaction enthalpy, and degree of cure over ageing time is presented. An iso-conversional model was developed to predict the cure progress at room temperature and under processing conditions. The viscosity of fresh and aged neat resin of CYCOM® EP2750 was investigated. A chemo-rheological model was proposed to predict the resin viscosity variation under different temperatures. The Williams-Landel-Ferry (WLF) model [4] was used to fit the experimental data. The model prediction was validated with experimental data from a reference cure cycle for the EP2750 prepreg.

The compaction behavior of the 2 x 2 twill weave CYCOM® EP2750 prepreg was studied at isothermal temperature of 120 °C using a stress relaxation method initially designed by Hubert [5]. The fiber bed compaction curve (effective stress–strain curve) was obtained. The stress–strain behavior predicted by Gutowski's model [6] closely matches the experimental results.

2. EXPERIMENTATION

2.1 Materials

The experimental study was carried out using the 2 x 2 twill weave CYCOM® EP2750 prepreg from Syensqo. It has a toughened epoxy resin system designed for high-volume cost-effective composite manufacturing. The material was provided by Syensqo and was stored in a freezer at -18 °C. Before testing, the material was taken out from the freezer and put at room temperature (RT) for 12-15 h prior to any cutting or sampling. Table 1 presents the materials specification.

Table 1. Material specifications

Characteristics	Specification
Material Name	CYCOM® EP2750
Resin Type	Epoxy

Fiber Type	Carbon Fiber
Weave Architecture	2 x 2 Twill
Resin Weight Content	39 %
Shelf-Life	12 months

To perform viscosity tests, it is easier to use the neat resin rather than the prepreg, since the presence of fiber can affect the apparent viscosity of the system and data interpretation. However, it was not possible to have access to the neat resin because of the complexity of the prepreg manufacturing process. Neat resin was then extracted using an in-house developed mechanical method. Once extracted, the glass transition temperature (T_g) of the neat resin was evaluated to be around -5 °C, corresponding to 4 % of degree of cure due to the extraction process itself.

2.2 Material ageing

Two types of material were prepared for ageing. First, a coupon of CYCOM® EP2750 prepreg was stored at room temperature (22 °C) and aged for 160 days. The humidity was monitored to be around 40 % RH during the full ageing study. Sub-samples were regularly extracted from the prepreg coupon and evaluated using DSC testing. Secondly, neat resin was extracted from the EP2750 prepreg. Samples of the extracted neat resin were stored in sealed cups and aged at room temperature (22 °C) for 20 days. Samples were taken regularly and evaluated with viscosity tests.

2.3 Material Characterization

2.3.1 DSC Measurements

The curing behavior and the T_g were studied using a combination of dynamic, isothermal, and modulated DSC measurements. DSC measurements were performed on the as-received and the aged CYCOM® EP2750 prepreg during 160 days at room temperature (RT). Each DSC test condition was carried out 3 times (repeats) with DSC 250 from TA Instruments, operating in the temperature range between -87 °C and 315 °C, under nitrogen purge. The sample mass was kept between 2 and 4 mg and used with T_{zero} hermetic pans. Dynamic tests were performed with five heating rates: 1, 2, 5, 10 and 15 °C/min. Dynamic DSC tests were performed to determine the cure kinetic model and to track the evolution of the T_g with the prepreg ageing at RT. Isothermal DSC experiments were performed at the following isotherms: 140, 150 and 160 °C. Finally, modulated DSC experiments were performed to investigate the relationship between T_g and degree of cure for this prepreg. Modulated DSC was performed with 1 °C modulation amplitude every 60 sec, following a ramp of 5 °C/min.

2.3.2 Viscosity Measurements

The rheological characterization of the CYCOM® EP2750 prepreg was performed with the neat resin after extraction and aged resin for 20 days at RT. All tests were carried out twice (2 repeats) using the Discovery hybrid rheometer HR 30 from TA Instruments. Tests were performed in the temperature range between 40 °C and 300 °C. Rheology tests were run with 25 mm disposal parallel plates and 1000 μm of gap. The oscillation strain and frequency were 1 % and 1 Hz respectively. Dynamic and isothermal scans were used to characterize the resin viscosity behavior and develop a predictive model. Rheology characterization was performed with temperature scans using the following heating rates: 0.5, 1, 2, 4 and 5 °C/min. Isothermal experiments were carried out at 110, 120, 130, 140 and 150 °C/min. Monitoring of the resin viscosity with ageing at RT was performed using temperature scan with a heating rate of 2 °C/min; and isothermal tests at 110 °C.

2.3.3 Fiber bed compaction tests

The flow compaction behavior of the prepreg during its molding process has a significant influence on the final part thickness, fiber volume content, and microstructure [7]. In the present work, the fiber bed compaction behavior is assessed directly from the 2 x 2 twill weave CYCOM® EP2750 prepreg, using a stress relaxation method developed initially by Hubert [5]. The curve shows the relationship between the fiber bed effective stress and its through-thickness strain. During through-thickness compression, an uncured prepreg can be considered as a nonlinear elastic fiber bed filled with a viscous resin [8]. When a hydrostatic pressure is applied on the prepreg, this loading is partitioned between the fiber bed and the resin as follows [8]:

$$P = \sigma_f + P_r \tag{1}$$

where P is the applied pressure, σ_f is the effective stress carried by the fiber bed, and P_r is the pressure in the liquid resin phase. When the resin is free to flow out of the prepreg without edge constraints, the resin pressure P_r will eventually become null and the applied pressure will be carried by the fiber bed only. The stress relaxation method works based on this principle.

2.3.3.1 Stress relaxation method

The stress relaxation method initially developed by Hubert is used in this work [9]. Note that this compaction curve is only valid if the in-plane fiber bed dimensions are not altered by experimental conditions, namely if the projected area of the fiber bed does not change during the trials as a result of fiber washout. Since the current EP2750 prepreg used here is based on a twill weave architecture and fibers are oriented in both X and Y directions, fibers could likely wash out along the resin flow direction. As a result, the main challenge of applying this method to the current prepreg is to determine the viable testing window (temperature, compaction rate, and compaction increment) where the viscosity is low enough for the resin to flow out while preventing fiber washout.

2.3.3.2 Test apparatus

The test apparatus used here (Figure 1) is similar to the one developed by Hubert [5]. The apparatus is mounted on an MTS 100kN Landmark servo hydraulic testing system. This apparatus consists of two main components: an upper piston and a bottom testing cavity, which have sliding fit tolerance to prevent material infiltration along the cavity walls. Eight distributed heating cartridges, controlled by temperature controllers, are used to achieve the desired test temperature. A linear variable differential transformer (LVDT) from Hoskin Scientific is installed next to the apparatus to obtain accurate displacement data. Two flush-mounted pressure sensors are installed to record the pressure gradient across the specimen, from the center to the edge. The MTS system is used to control the displacement while measuring the load applied to the specimen.

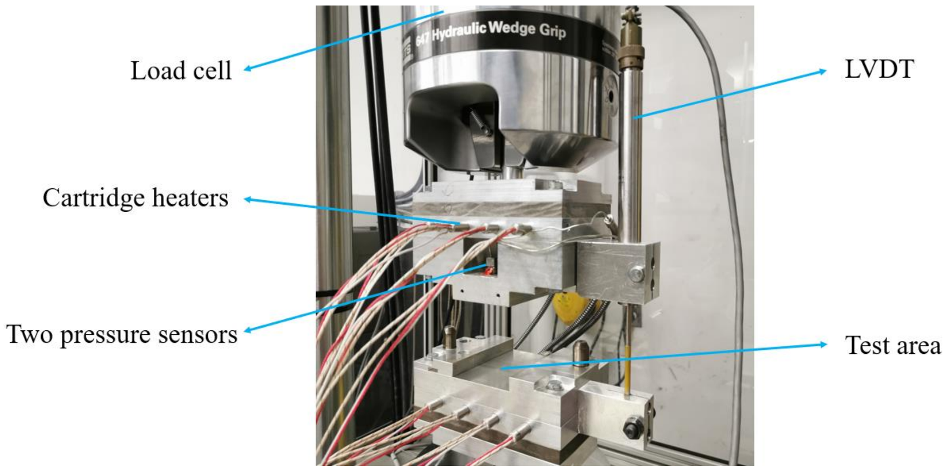


Figure 1. Test apparatus for the fiber bed compaction test.

2.3.3.3 Test procedure

The specimens were prepared by laying up 10 plies of twill weave CYCOM® EP2750 prepreg. Specimen dimensions in the x-y plane were 76.2 mm x 63.5 mm. The selected coordinate system is shown in Figure 2. The width of the specimen (63.5 mm) is the same as the width of the testing area, so the fiber bed deformation in the y direction was constrained by the cavity walls, and the resin was forced to flow in the x direction only.

Before testing, the prepregs were taken out of the freezer and thawed at RT. A room temperature debulking process was performed on every specimen under full vacuum for 5 minutes in order to remove layup bulk as well as air gaps. The length, width, thickness, and mass of each specimen were measured prior to each test and these samples were wrapped by a thin Teflon film to prevent any sticking to the jig, as shown in Figure 2.

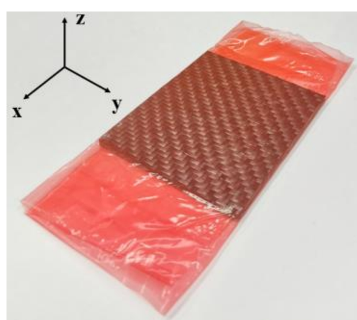


Figure 2. Specimen is wrapped around in a thin Teflon film.

Trial-and-error tests were carried out to determine the proper test parameters. An isothermal testing temperature of 120 °C was selected based on the cure kinetics data and the viscosity data, to lower the resin viscosity while ensuring an adequate testing time window before the resin starts to gel. Compaction rates of 0.1 mm/min (for the first compaction step), and 0.08 mm/min (for the rest compaction steps) were chosen to make sure there was no fiber washout. The test results and the development of fiber bed compaction curve are presented in Section 3.5.

3. RESULTS AND DISCUSSION

3.1 DSC data

The investigation of the T_g was conducted with DSC runs. The average initial T_g values for the fresh as-received prepreg was assessed to be -9.1 ± 0.1 °C. The average initial residual enthalpy of the as-received prepreg was estimated to be 187.2 J/g ± 7.4 J/g. The T_g of the uncured prepreg was then considered around -9.1 °C, and its evolution was monitored over time at RT. Figure 3 shows the evolution of the T_g over time at RT.

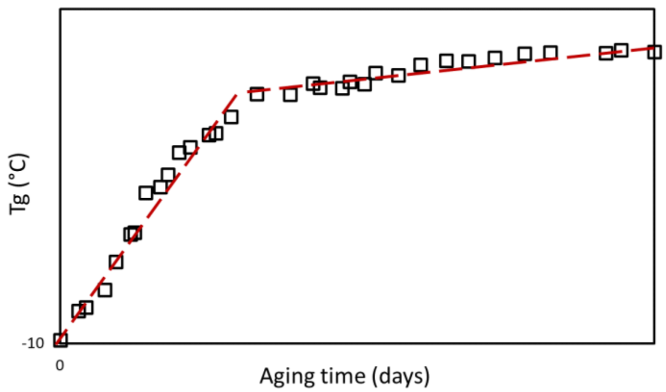


Figure 3. Evolution of the T_g values over the ageing time at room temperature.

Two main regions were observed regarding the T_g evolution at RT. In the first one, the T_g increases linearly over time. In the second one, a slower evolution of the T_g over time is observed. This can be explained by a decrease in the resin reactivity caused by the slow progression of the crosslinking at RT. Similar results were found in the literature for epoxy systems aged at RT [10]. The cure progress at RT leads to a drop of curing agent [10,11] and volatile concentration [12] over time.

3.2 Development of the kinetic model

The cure process for the thermoset resin system exhibits very complex mechanisms and steps involving chemical and physical changes of the system while curing. The curing process consists in a series of chemical reactions leading to the increase of the crosslinking among the thermoset polymer system with the heating temperature. The cure kinetics model was developed from the measurements of the heat released during cure using dynamic and isothermal DSC tests. One can consider α as the degree of cure (DOC) and is defined as follow:

$$\alpha = \frac{\int_{T_0}^{T_f} \frac{dH}{dt}\, dT}{\Delta H_T} \tag{2}$$

Equation (2) expresses the fraction of the released heat at any time during polymerization reaction with respect to the total heat released by this reaction ΔH_T. The determination of the total heat of reaction (ΔH_T) was obtained from dynamic DSC tests. Figure 4 shows the dynamic DSC tests performed with the as-received prepreg using different heating rates. The DSC thermograms highlight the exothermic reaction of polymerisation starting in the vicinity of 120°C.

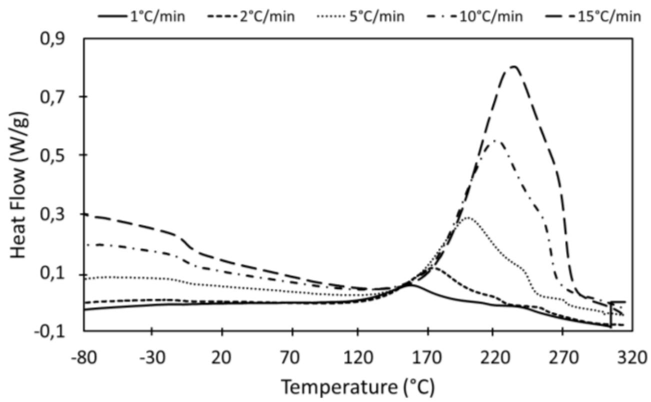


Figure 4. Dynamic DSC tests of the as received prepreg EP 2750.

The cure kinetics model was developed using AKTS Thermokinetics software. The conversion rate for thermoset resin system is generally expressed as follow:

$$\frac{d\alpha}{dt} = K(T)f(\alpha) \tag{3}$$

where α is the degree of cure (DOC) or the conversion rate, K and *f* are function of the temperature and the DOC, respectively. The function K can be assumed to exhibit an Arrhenius dependency on temperature and can be expressed as follow:

$$K(T) = A\exp(-\frac{E}{RT}) \tag{4}$$

where A is the pre-exponential factor, E the activation energy, R the gas constant and T the absolute temperature. From the literature, different models can be found to describe the cure kinetics of thermoset resin systems [13–15]. Among these approaches, the isoconversional model is a conversion dependent approach that consider only the reaction activation energy E and the conversion rate α [16]. When derived from the logarithmic deviation, Equation (3) gives the following relationship:

$$\ln(\alpha) = \ln A\, f(\alpha) - \frac{E}{RT}\,(\alpha) \tag{5}$$

Equation (5) describes the isoconversional model and it is used to fit dynamic and isothermal DSC measurements. Figure 5 shows the variation of the activation energy with the progression of DOC.

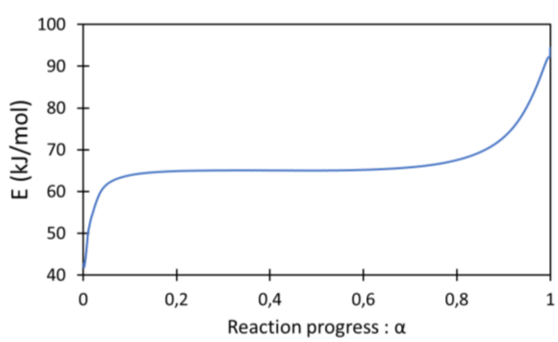


Figure 5. Variation of the activation energy with the reaction rate.

As the reaction progresses, the activation energy of the curing reaction evolves. The evolution of the activation energy is described by 3 main zones. A slight increase is observed at the beginning till 10% of conversion. Between 10% and 70% of conversion, the activation energy exhibits a plateau, and it starts to increase from 80% of conversion. The initial increase of the activation energy is due to the reaction initiation as a result of the autocatalytic characteristics of the reaction. The curing process induces an increase of the molecular weight of the polymer and a decrease of the autocatalytic characteristics of the reaction [17]. Thus, higher activation energy is needed to promote full extent of crosslinking of the resin system.[17].

Figure 6 shows the comparison between the experimental data and the prediction from the cure kinetics model for the dynamic DSC tests on the prepreg. This figure shows the good adequacy between the experimental results and the model.

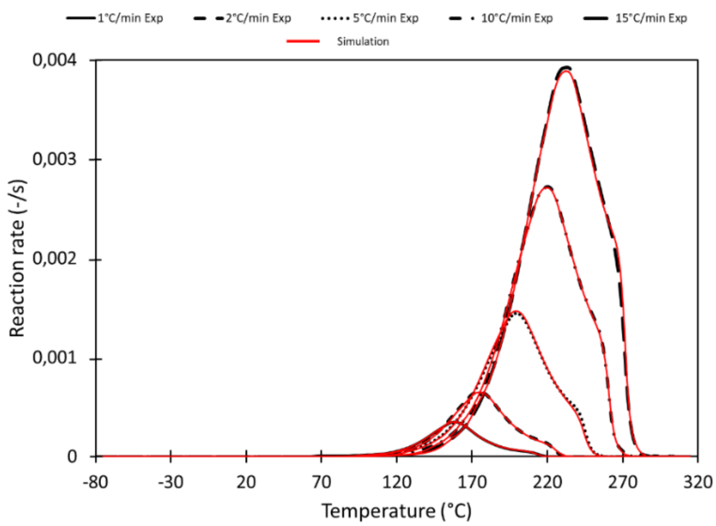


Figure 6. Experimental data and model prediction for dynamic cure on the EP2750 prepreg.

To validate the kinetics model described previously, isothermal DSC runs were performed at 140 °C, 150 °C and 160 °C. The isoconversional model was used to predict the reaction kinetics and simulate the progression of the isothermal cure. Figure 7 shows fair agreement between the simulated data and the experimental ones.

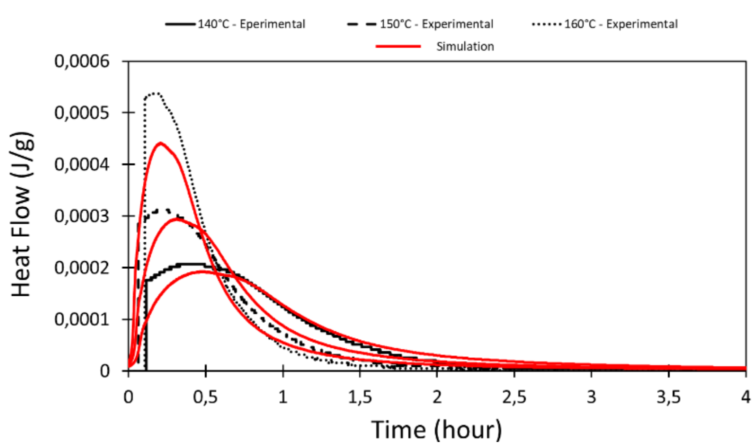


Figure 7. Experimental data and model validation for isothermal cures on the EP2750 prepreg.

3.3 Dependency between T_g and DOC

Curing of the resin leads to an increase of the crosslinking density in the resin system and a rise in T_g. The evolution of T_g during ageing was evaluated from dynamic DSC tests as presented in Section 3.1. For intermediate cure states, the T_g was determined using multistep DSC approach. The procedure consists of holding an isothermal step for a certain amount of time to cure the sample at an intermediate α, then applying a ramp to the next isothermal. This relies on the fact that the cure kinetics model of the polymer system is known *a priori*. Finally, the T_g of highly cured states ($\alpha \geq 0.7$) was determined using modulated DSC measurements. The corresponding DOC was evaluated by two ways. First, DOC was experimentally determined from the heat generated by the reaction, considering ΔH_T to be 187.2 J/g ± 7.4 J/g. DOC was also predicted using the cure kinetics model for different intermediate states. The $T_{g\infty}$ of the fully crosslinked system was determined after curing the prepreg at 180 °C for 30 min and then post-curing it for 2 h at 180 °C. Figure 8 shows the evolution of the T_g as a function of the conversion rate α.

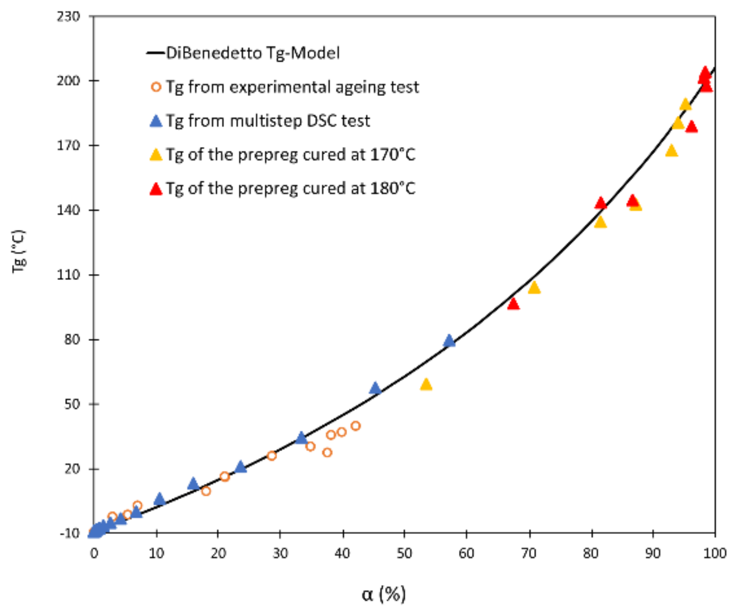


Figure 8. Relationship between the T_g and α of the CYCOM® EP2750 prepreg.

The dependency between T_g and α was fitted using DiBenedetto model [18,19], showing a good agreement between experimental ones and this model. The DiBenedetto model is given by the following relationship:

$$\frac{T_g - T_{g,0}}{T_{g,\infty} - T_{g,0}} = \frac{\lambda\, \alpha}{1 - (1 - \lambda)\alpha} \tag{6}$$

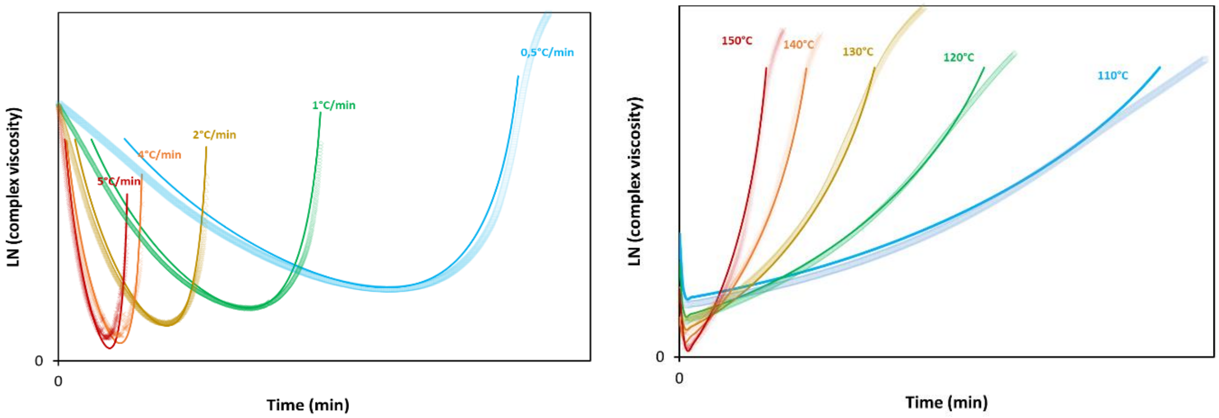
where $T_{g,0}$ and $T_{g,\infty}$ are the glass transition temperatures of as-received and fully crosslinked system respectively, α is the DOC and λ is a model factor determined by nonlinear regression to be 0.5026.

3.4 Development of the viscosity model

The analysis of the rheological behaviour of this resin system was investigated during resin cure. As the cure takes place, the molecular weight of the resin increases significantly leading to a decrease of the polymer mobility and an increase in the system viscosity. The polymer temperature can influence its chain mobility as well and impacts its viscosity. Hence, the resin viscosity is dependant on temperature as well as DOC. Dynamic rheological tests were first performed on the extracted neat resin from as-received prepreg using 5 different heating rates. The Williams-Landel-Ferry (WLF) [4] model was applied to fit the experimental data. The WLF equation is an empirical approach to determine the temperature-induced physical changes in polymer systems. The WLF model is expressed by the following expression:

$$\eta(T,\alpha) = \eta_g \exp\left[-\frac{C_1\,(T - T_{g,0})}{C_2 + T - T_{g,0}}\right]\left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^n \qquad (7)$$

where, η is the system viscosity, η_g is the viscosity at the glass transition, C_1 and C_2 are constants of the equation, α and α_g are the current DOC and the DOC at gel point respectively, and n is an exponent. Figure 9 shows the viscosity variation over time for dynamic and isothermal tests. Good agreement is found between the experimental data and the model prediction.

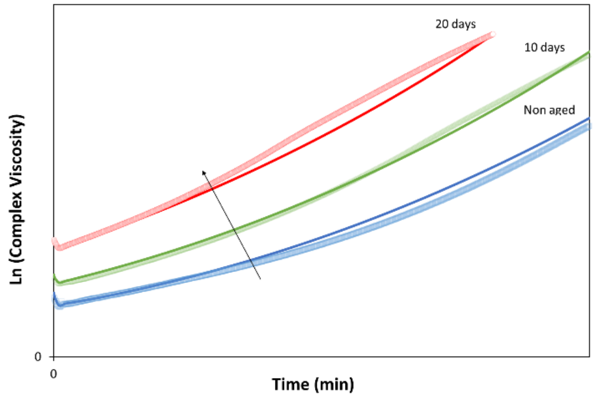


(a) (b)

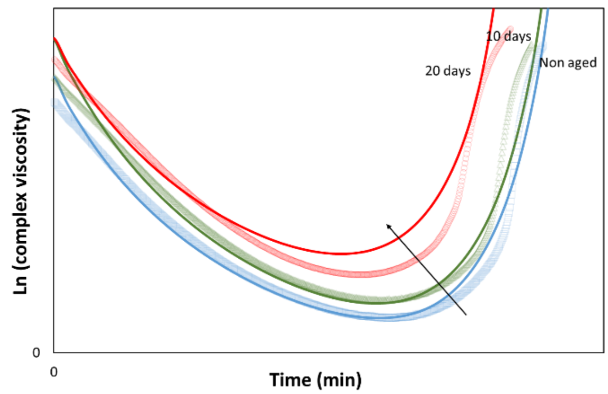
Figure 9. Complex viscosity as a function of time, in logarithmic scale, for (a) dynamic and (b) isothermal tests with the chemo-rheological model data.

The resin viscosity behaviour follows a typical "U" shape profile. Initial viscosity decreases as a result of temperature increase till reaching a minimum. Higher the heating rate and the curing temperature are, lower the minimum viscosity is. Afterwards, resin viscosity starts to increase as a result of crosslinking (DOC) [20]. The gel point occurs during the viscosity rise and it was identified as the crossover point between G' and G'' curves. The model parameters were determined using nonlinear regression on all experimental data.

The resin system being very reactive at RT, the evolution of its viscosity during storage at RT was also investigated. Figure 10 shows the evolution of the resin rheology during ageing, being monitored with isothermal and dynamic viscosity tests.



(a)



(b)

Figure 10. Complex viscosity as a function of time, in logarithmic scale, for (a) isothermal test at 110 °C and (b) dynamic test at 2 °C/min with the chemo-rheological model data.

Experimental data was fitted with the WLF model presented previously and fair agreement was found between experiments and model prediction. A slight offset between experiments and model prediction is observed though. The WLF model captures well the overall behavior of the resin viscosity after short duration ageing. However. the model prediction is less accurate for long duration ageing (20 days). Figure 11 shows resin viscosity profiles for non-aged and aged prepreg with respect to a reference cure cycle. This reference cure cycle represents a typical fast consolidation press process recommended by Syensqo for the material under evaluation. Fair agreement was observed between experimental and model prediction.

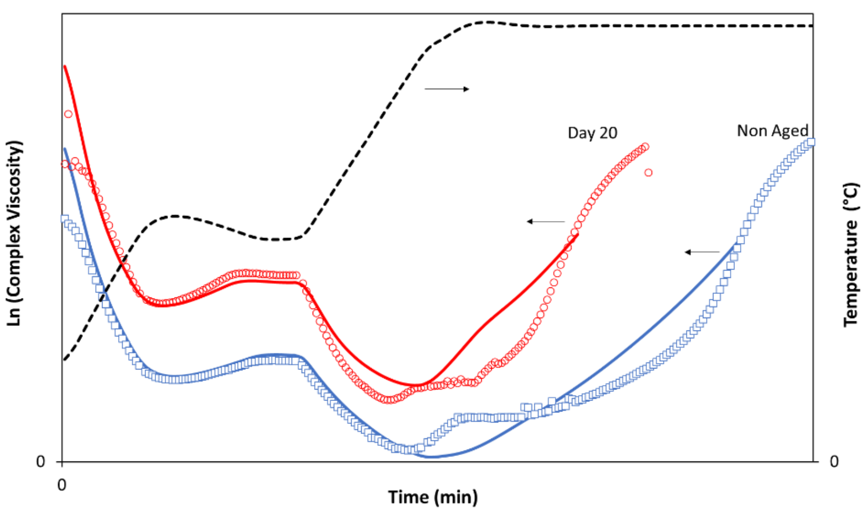


Figure 11. Typical cure cycle viscosity results for the EP2750 prepreg non-aged and after being aged for 20 days at RT.

3.5 Development of the fiber bed compaction curve

Fiber bed compaction tests were carried out on the 2 x 2 twill weave CYCOM® EP2750 prepreg at 120 °C using the stress relaxation method described in Section 2.3.3. A typical test result for a 2.72 mm thick specimen (10 plies) is presented in Figure 12.

The load relaxation takes about 6 to 10 minutes in the first 3 steps. In the last step, the displacement is held for a longer duration to ensure load stabilization (no further decrease). Since load relaxation takes a relatively longer time compared to Hubert's work [9], only 4 compaction steps could be included into one testing window of 50 minutes before the viscosity becomes too high. Therefore, bigger displacement increments were used in the tests to reach a detectable amplitude of relaxed load and a significant fiber volume content at the end. The displacement was 0.6 mm in the first step, which corresponding to a compressive strain of 22.1 %. Relaxation steps with lower strains and their corresponding loads were missing in this trial. As a result, two other tests were performed on specimens compressed to 5.5 % and 14.9 % strain respectively (Figure 13).

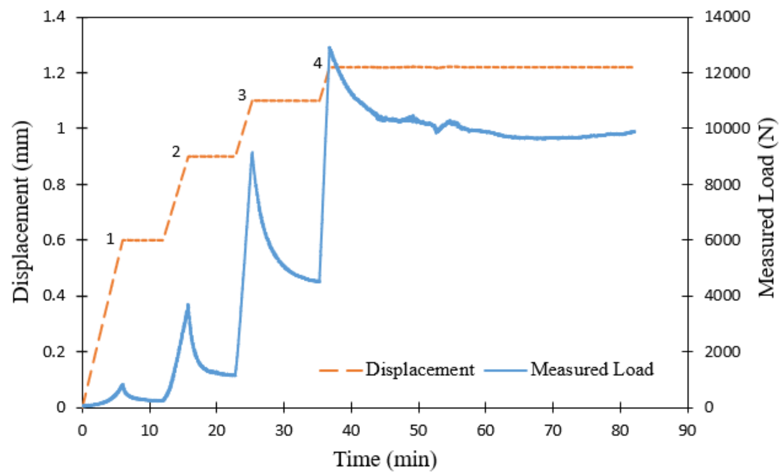


Figure 12. A typical test result with 4 displacement increments and the measured load with time, showing the load relaxation during displacement hold.

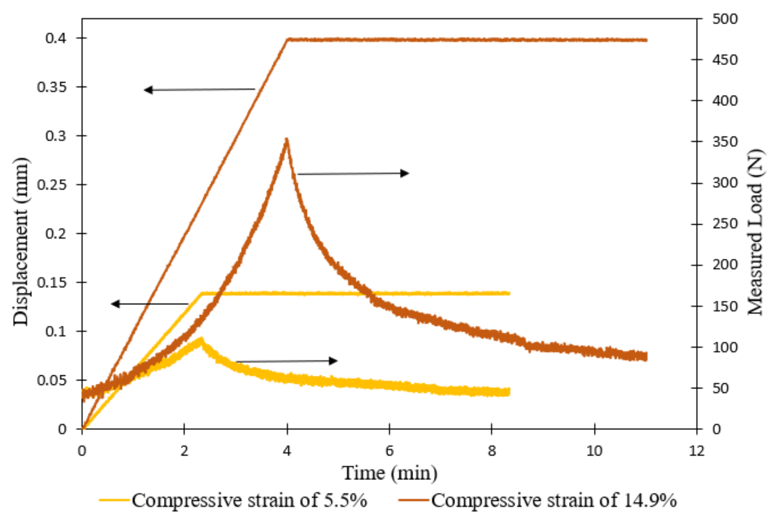


Figure 13. Two tests which compressed specimens to strain of 5.5 % and 14.9 % respectively.

The measured load in Figure 12 can also be plotted against displacement, as shown in Figure 14. The four displacement steps and their corresponding relaxed loads were extracted to construct the load-displacement curve for CYCOM® EP2750 prepreg, which is the dashed line in Figure 14.

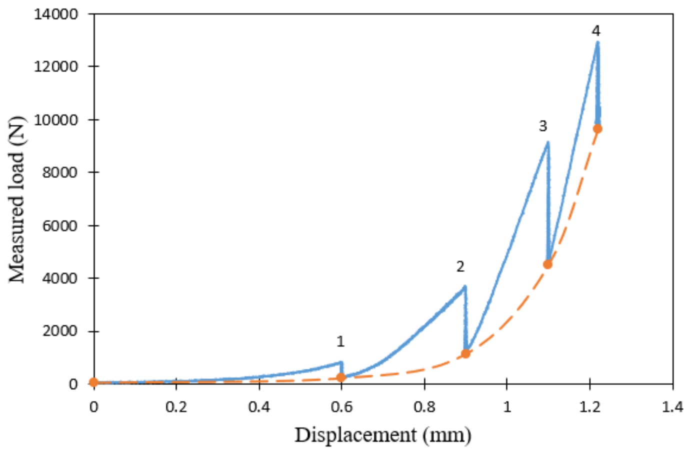


Figure 14. Load-displacement curve (dashed line) is constructed from displacements and the corresponding relaxed load.

Knowing the projected area and initial thickness of these specimens, a stress-strain master curve was constructed from displacement and relaxed load data, which is presented as the red dots in Figure 15. It was found that the Gutowski's model [6] was adequately describing this fiber bed compaction curve for 2 x 2 twill weave CYCOM® EP2750 prepreg. The original equation expresses the fiber bed effective stress as a function of the fiber volume fraction:

$$\overline{\sigma}(V_f) = \frac{3\pi E_f}{\beta^4} \frac{\left(1 - \sqrt{\frac{V_f}{V_{f0}}}\right)}{\left(\sqrt{\frac{V_a}{V_f}} - 1\right)^4} \tag{8}$$

where E_f is the flexural modulus of the fiber tow, β is the waviness ratio, V_f is the fiber volume fraction at the current compaction level, V_{f0} is the initial fiber volume fraction, and V_a is the maximum fiber volume fraction achievable. Note that E_f and β are unknown for CYCOM® EP2750 prepreg. For simplicity's sake, $\frac{3\pi E_f}{\beta^4}$ is considered as a specific fiber bed property which is constant and is rewritten as A. $\frac{V_f}{V_{f0}}$ and $\frac{V_a}{V_f}$ can both be rewritten as a function of fiber bed compressive strain ε_f. Therefore, the Gutowski's model can be rewritten as:

$$\overline{\sigma}(\varepsilon_f) = A \frac{\left(1 - \sqrt{\frac{1}{1+\varepsilon_f}}\right)}{\left(\sqrt{\frac{1+\varepsilon_f}{1+\varepsilon_{max}}} - 1\right)^4} \tag{9}$$

where $A = \frac{3\pi E_f}{\beta^4}$, ε_{max} is the maximum fiber bed strain achievable.

The stress–strain prediction by the Gutowski's model with $A = 10.12$ and $\varepsilon_{max} = 61.6\ \%$ is plotted in Figure 15, which shows a fair agreement with the experimental data. Therefore, the Gutowski's model can adequately describe the compaction behavior of EP2750 prepreg.

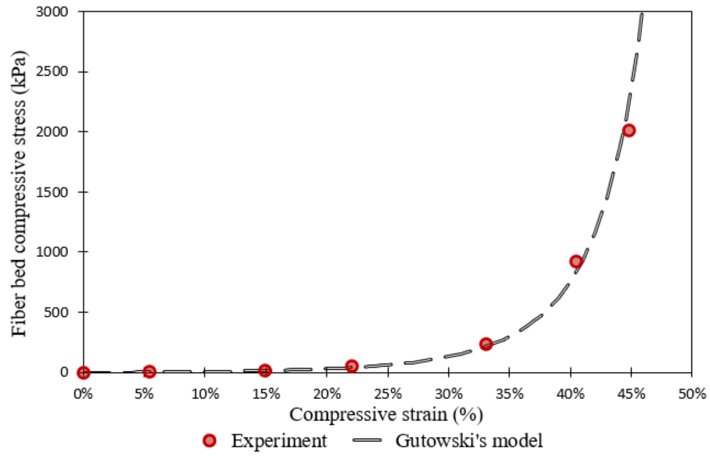


Figure 15. The fiber bed compaction curve for 2 x 2 twill weave CYCOM® EP2750 prepreg compared with the prediction by the Gutowski's model.

4. CONCLUSION

In this study, the behaviour of the 2 x 2 twill weave CYCOM® EP2750 prepreg was investigated for as-received material and after being aged at room temperature. Cure kinetics was studied by DSC analysis and was described using the iso-conversional approach. The model was able to predict cure progress at room temperature as well as under typical processing conditions. Resin viscosity was investigated using oscillatory rheology. The resin viscosity was also monitored during ageing at room temperature. A chemo-rheological model was proposed to predict the resin viscosity evolution over time and temperature. The Williams-Landel-Ferry (WLF) model was used to fit the experimental data. The model prediction was validated using a reference cure cycle. The fiber bed compaction behavior of the 2 x 2 twill weave CYCOM® EP2750 prepreg was obtained from compaction tests using stress relaxation method. The Gutowski's model was adequately describing the compaction behavior of this prepreg.

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