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Short-term Creep Behaviour of Different Polymers Used in Additive Manufacturing under Different Thermal and Loading Conditions

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Polymer materials produced by additive manufacturing undergo significant changes in their dimensions under continuous loading conditions. This situation affects the operation of polymer structures produced by additive manufacturing within safe limits. Therefore, it is crucial to determine the creep behaviour of polymers produced by the additive manufacturing method. This study investigates the creep behaviour of six different materials, acrylonitrile butadiene styrene (ABS), chlorinated polyethylene (CPE), polylactic acid (PLA), tough polylactic acid (TPLA), polycarbonates (PC), and nylon most commonly used in additive manufacturing. The creep test specimens are firstly produced with a three-dimensional (3D) printer, and then their final dimensions are given using computer numerical control (CNC) milling. The creep experiments are carried out at three different ambient temperatures (25 °C, 40 °C, and 60 °C) and two different stress levels (10 MPa, 20 MPa). According to the test results, it was determined that the material type, temperature, and loading levels significantly influenced the creep behaviour of the 3D printed polymer materials.

Keywords: Additive manufacturing, creep experiments, polymer materials, thermal effect

Highlights

- *Creep test specimens are produced with a 3D printer and CNC milling.*
- *Creep tests are performed for different temperatures and loading conditions.*
- *Short-term creep behaviours of polymers are investigated experimentally.*
- *Material type, heat, and loading significantly affected the creep behaviour of the polymer materials.*

0 INTRODUCTION

Fused deposition modelling (FDM) is a production method that allows parts to be processed layer by layer and produced as one piece. As a basic principle, in FDM, the raw material is heated, fluidized, and passed through a nozzle to produce the part in layers. With this production technique, products that cannot be produced in one step with traditional production methods have become easily produced. The FDM technique has started to increase its importance in practical life day by day with the increase and cheapening of three-dimensional (3D) printers. The advantages of FDM are summarized by Ngo et al. [1] as design freedom, customization, waste minimization, and the ability to produce complex structures.

The FDM method allows many different polymer materials to be used in 3D production. PLA, TPLA, ABS, PC, nylon, and CPE are the most commonly used polymer materials in the studies carried out with the FDM method in the literature. PLA is the most commonly used biopolymer and thermoplastic produced from corn starch and sugar cane in 3D printing. PLA enables fast and reliable 3D production with high surface quality [2]. ABS is also commonly used in 3D printing; it is tough and durable, provides high dimensional stability, and is resistant to physical impacts and chemical corrosion [3]. PC is a thermoplastic with a wide range of uses in the modern manufacturing industry; it can be defined as strong, temperature resistant, and tough. PC provides high mechanical strength, ultimate printing quality, and thermal resistance up to 110 °C [4]. Nylon is well known for good elongation, abrasion resistance, high strength-to-weight ratio, and low friction coefficient but a much lower strength [5]. Compared to other materials, the use of CPE with FDM is limited. CPE is defined as chemically resistant and tough [6].

The determination of the mechanical properties of the products produced using the FDM method has attracted great interest with the widespread use of FDM technology. Thus, many researchers have carried out extensive studies on the determination of the mechanical properties of the products produced by FDM. In these studies, generally, the tensile [7], bending [8], and impact [9] strengths of materials produced by the FDM method are experimentally investigated. While the mechanical properties of different materials have been investigated [10], the effects of FDM process parameters on mechanical properties have also been studied [11]. In addition, the fatigue strength of the materials produced with 3D printers has been experimentally investigated [12].

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Creep is the permanent deformation that occurs over time in materials under the influence of a constant temperature, stress, or loading. The creep behaviour of polymer materials is significant in industrial applications where dimensional stability is essential. For this reason, the creep behaviour of polymer materials should be determined, and the designs should be carried out accordingly. Many studies examine the creep behaviour of different polymer materials in the literature. Generally, the researchers are focused on the effects of the printing process parameters on the creep behaviour of the 3D printed materials. Zhang et al. [13] investigated the tensile, creep, and fatigue behaviour of the 3D printed ABS samples. The effects of the printing orientation on the creep properties of the ABS test samples were defined experimentally. The effect of printing orientation on short-term creep behaviour of the 3D printed PLA samples is investigated in another comprehensive study [14]. In addition, the effects of layer thickness and different PLA types on creep are investigated experimentally. Mohammed et al. [15] investigated the flexural creep stiffness behaviour of PC-ABS material produced with FDM. In another study, the authors experimentally investigated the effects of process parameters on the creep and recovery behaviours of samples produced using the FDM method [16]. The creep and recovery behaviour of the reinforced 3D composites are investigated by Al Rashid and Koç [17]. Waseem et al. define the most effective process parameters on the tensile creep behaviour of the 3D printed PLA parts. They proposed the optimal combination of the process parameters using categorical response surface methodology [18]. Some researchers have experimentally investigated the effects of environment variables on creep. Temperature-humidity [19] and creep load [20] are considered variable parameters when these studies are examined. Various models have been used to predict creep in some studies. Lim et al. [21] developed a long-term creep model using the short-term creep test results for PC and ABS. Ye et al. [22] proposed a modified Burger model to predict the creep behaviour of the 3D printed test samples. The proposed model is validated with the creep experiments. As a result of the study, the modified model can accurately calculate the creep behaviour of the PLA-max samples with different printing angles.

According to the literature review, it is seen that the effect of process parameters on the creep behaviour of materials produced by the FDM method has been generally investigated. No study has been found that investigated the creep behaviour of different materials produced by the FDM method. In addition, temperature is one of the most influential parameters on the creep behaviour of the polymer materials. Similarly, when the literature is examined, the studies examining the effects on the creep behaviour of the samples produced with FDM temperature are very limited. These shortcomings in the literature have been the biggest motivation for this study.

The present investigates the creep behaviour of six different polymer materials (ABS, CPE, PLA, TPLA PC, nylon) produced by the FDM method. In addition, experiments are carried out for each material type at three different temperatures (room temperature, 40 °C, and 60 °C) and two different stress levels (10 MPa and 20 MPa). The effect of temperature and stress on the creep behaviour of materials produced by the FDM method has been explained.

1 MATERIAL METHOD

2.1 Production of Creep Test Specimens

In this study, the creep behaviour of the different polymer materials produced with a 3D printer was experimentally investigated. The polymer test specimens were produced by combining FDM and CNC milling operations. The creep test specimens were produced with the Ultimaker 2+ Extended 3D printer. The printing area is 230 mm × 230 mm × 305 mm, and the resolution is 12.5 µm – 12.5 µm – 5 µm for the $x – y – z$ axes, respectively. The dimensions of the creep test specimens were determined according to ASTM D638 Type IV [23]. The computer-aided design (CAD) data of the test specimens were created in Solidworks software. The designed data were converted into the stl file format and sent to the Ultimaker Cura (version 4.13.1) software to define the 3D printing parameters. The G – codes of the test specimens were created in Ultimaker Cura software. The manufacturing parameters of the test specimens determined in Ultimaker Cure are given in Table 1.

The creep test specimens were produced with the Ultimaker brand filaments with a diameter of 2.75 mm. The 3D printing parameters of the test samples were defined according to the manufacturer's technical data sheets [24] to [29]. The test samples were produced with the same G – codes and one by one in the middle of the printing table in order to produce the test samples as similar as possible. Each specimen was produced three times for the repeatable experiments.

When the samples are produced in a 3D printer, the notch effect and different wall pattern geometries

Table 1. *3D printing parameters of the test samples*

Material	Extrusion temperature [°C]	Table temperature [°C]	Printing speed [mms^{-1}]	Nozzle diameter [mm]	Layer thickness [mm]	Infill density [%]	Infill pattern
PLA [24] (Pearl-White)	200	60	60	0.4	0.2	200	Lines
ABS [25] (Yellow)	230	80	55				
Nylon [26] (Black)	245	60	45				
PC [27] (Transparent)	270	110	45				
CPE [28] (Yellow)	240	85	45				
TPLA [29] (Black)	205	60	60				

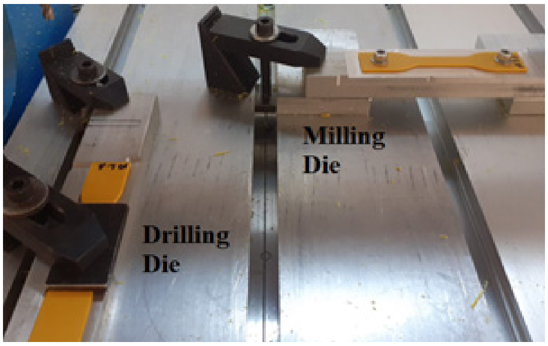
occur on the test samples. To eliminate this problem, the creep test samples were subjected to CNC milling after the 3D printing process, minimizing the notch effect and possible size and dimensional defects. The CNC milling process was completed in two steps. First, holes were drilled to connect the specimens to the creep test device. Then, 2 mm from the outer region of the creep test specimen was machined to achieve a homogeneous structure. To carry out these operations, two special drilling and milling dies were designed and produced. The produced special drilling and milling dies are seen in Fig. 1a.

Creep test specimens produced with a 3D printer for CNC milling were produced in sizes 2 mm larger than the dimensions specified in ASTM D638 Type IV. After the CNC milling process, the samples were brought to the dimensions in ASTM D638 Type IV (Fig. 1b). Four flutes milling cutter, with 6 mm diameter, were used in both drilling and milling operations. The cutting direction is defined as climb. The spindle speed is selected at 3500 rpm, and the x-, y-axis speeds are defined as 500 mm/min.

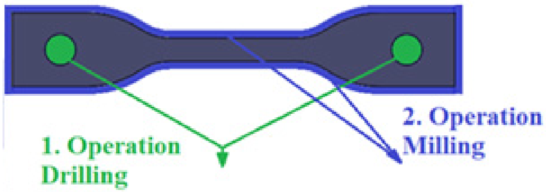
2.2 Creep Tests

The primary purpose of this study is to determine the creep behaviour of different polymer materials produced in 3D printers with the FDM method under different temperatures and loads. Various creep tests have been carried out to achieve this aim. The experiments were performed on the standard creep test device shown in Fig. 2. As seen in the figure, two measurement devices on the creep test device measure the temperature and the amount of test sample elongation. An Etopoo brand electronic micrometer was used to measure the time-dependent creep deformations of the test samples. The micrometer can measure between 0 mm to 12.7 mm with an accuracy of 1 µm. The temperature of the test area was measured instantaneously with the PT100 temperature sensor. This sensor can measure the temperature between –50 °C and 250 °C with an accuracy of 0.1 °C. The temperature and elongation data collected over the temperature sensor and micrometer are sent to the PLC module on the creep tester. The data on the PLC module is instantly transferred to the computer environment. The data transmitted to the computer environment can be obtained in Excel format with the software of the creep test device.

Creep tests were carried out as specified in the ASTM D2990-17 [30] standard. Moreover, the creep tests were performed in a climate-controlled room and on a vibration-insulated table. The creep tests were performed for three different temperatures (25 °C, 40 °C, and 60 °C) and two various stress levels (10 MPa and 20 MPa). The temperature is set to the



a)



b)

Fig. 1. *Production of creep test specimens; a) produced drilling and milling dies, and b) machining stages*

Fig. 2. *General view of the creep test device and detailed view of the test region*

desired level in the creep tests, and the heater starts to heat the test area. When the ambient temperature reaches the desired temperature, the heater turns off. If the ambient temperature drops 1 degree below the desired temperature, the heater works again and brings the environment to the desired level. In this way, the ambient temperature is controlled with minimal fluctuations. Creep tests are started when the test zone temperature reaches equilibrium at the desired temperature. Experiments begin by lowering the protective latch, and temperature and elongation data are instantaneously collected and recorded from the computer environment. Each creep test was carried out for 3 hours (10800 s); during this time, the creep elongation was measured and recorded with a micrometer.

2 RESULTS AND DISCUSSIONS

This study performed creep tests for six different materials (ABS, PLA, TPLA, CPE, PC, and nylon) under three different temperatures and two different loading conditions. Each experiment was repeated until three successful results were obtained. The amount of elongation obtained depending on time has been interpreted by presenting different graphs. Result graphs were created by considering the test result closest to the mean for each material, temperature, and loading condition. Short-term creep behaviours (primary and secondary creep phases) of different materials are investigated in this study. Tertiary creep behaviour is also seen under specific ambient temperature and stress levels in some cases. However, this study is mainly interested in the short-term creep behaviour of different polymers.

The creep test results for ABS material for different ambient temperatures and stress levels are seen in Fig. 3. The creep characteristic's first and second stages can be seen for all tests except the 60 °C and 20 MPa case. The ABS sample ruptured quickly in approximately 3 min at 60 °C temperature and 20 MPa stress conditions. The first stage creep region extends over a longer period with the increase in temperature. In the first creep stage, the sample elongates due to the

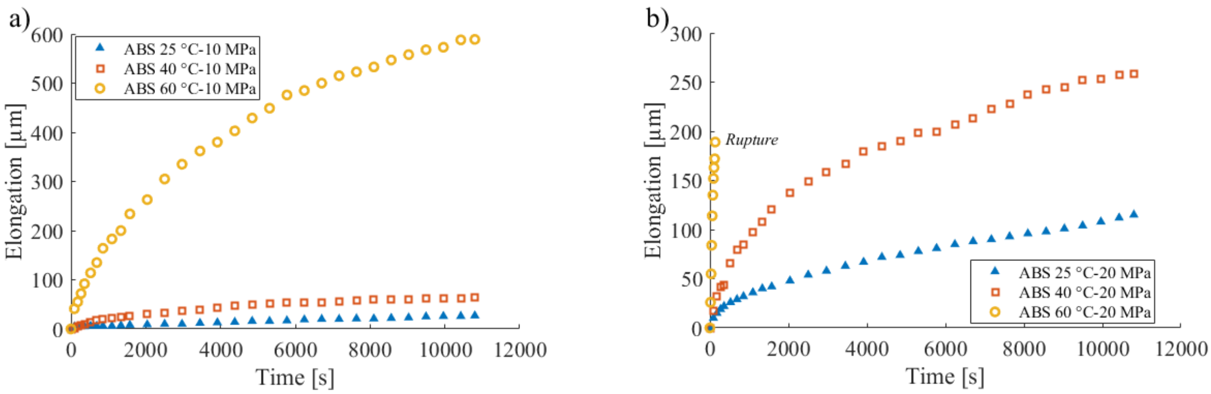


Fig. 3. *Creep test results of ABS under different ambient temperatures for; a) 10 MPa, and b) 20 MPa stress levels*

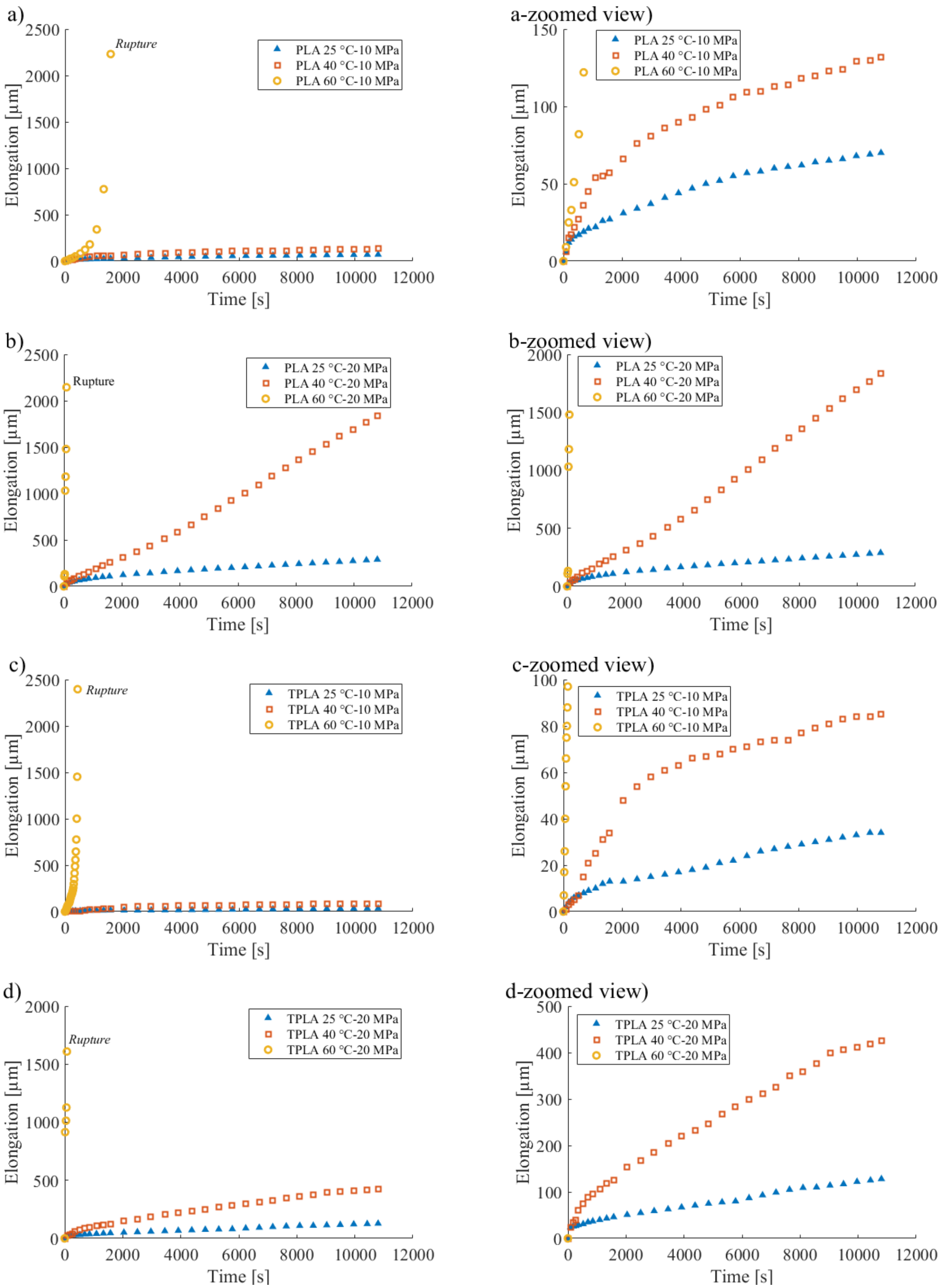


Fig. 4. *Creep test results of PLA and TPLA under different ambient temperatures and stress levels; a) 10 MPa PLA, b) 20 MPa PLA, c) 10 MPa TPLA, and d) 20 MPa TPLA (left column normal, right column zoomed views)*

effect of the load, where the dislocation movements are pretty large. As the temperature increases, the first stage creep zone expands because the ability to move on dislocations in the material increases. The creep resistance of the ABS material decreases with the increase in the ambient temperature and stress levels.

Fig. 4 indicates the creep test results for PLA and TPLA for different ambient temperatures and stress levels. As the figures are unclear at high temperatures and loads, a zoomed-in view of each figure is shown in the right column of the Fig. 4. The creep samples produced from PLA are exposed to much more creep under the same test conditions than the samples produced from ABS. It is determined that the increase in temperature and applied load reduces the creep strength of the samples produced from PLA more than ABS samples. In addition, it has been tested that the sample breaks after a while in the case of 60 °C and

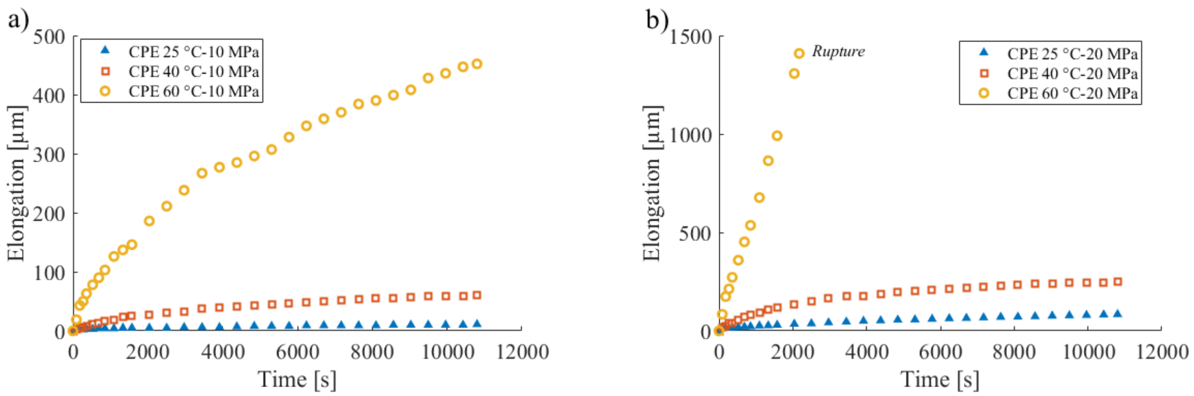


Fig. 5. *Creep test results of CPE under different ambient temperatures for; a) 10 MPa, and b) 20 MPa stress levels*

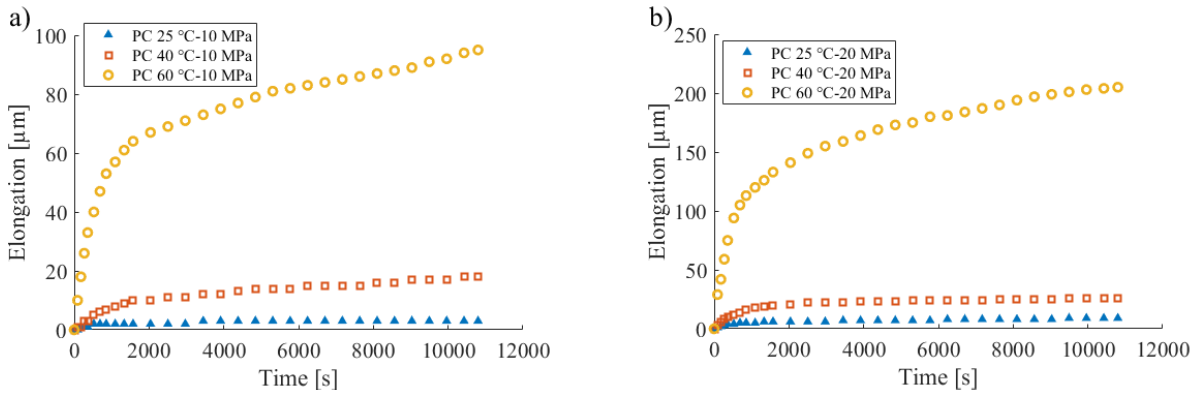


Fig. 6. *Creep test results of PC under different ambient temperatures for; a) 10 MPa, and b) 20 MPa stress levels*

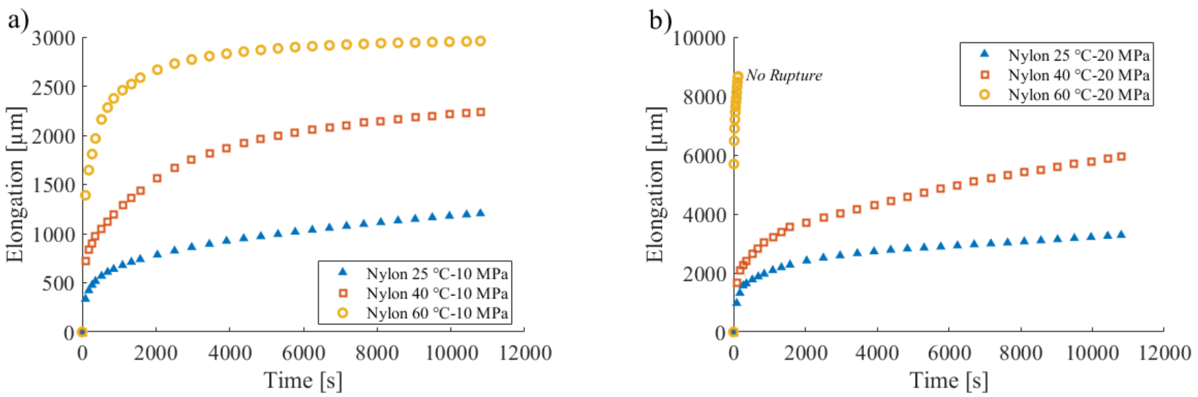


Fig. 7. *Creep test results of nylon under different ambient temperatures for; a) 10 MPa, and b) 20 MPa stress levels*

10 MPa. However, the time to rupture is much longer than the 60 °C – 20 MPa case. According to the test results, although PLA is the most commonly used polymer in additive manufacturing, its creep strength is quite low. It can be said that both temperature and load significantly reduce the creep strength; therefore, parts made of PLA material are suitable for use at room temperature and very low constant loads. Similar to ABS and PLA materials, the creep increases in creep test specimens produced from TPLA with the increase in ambient temperature and load. When the total creep values are examined, the samples produced from TPLA showed less creep than PLA but more than ABS. The creep test samples were damaged quickly under both loading conditions at 60 ˚C. In short, the TPLA material has better creep strength than PLA and worse strength than ABS.

Fig. 5 illustrates the creep test results of CPE test samples under different ambient temperatures and stress levels. Similar to other materials, the creep rate of the CPE increases with the increase in the ambient temperature and stress levels. However, the creep resistance of the CPE materials is better than ABS, PLA, and TPLA. The CPE creep test samples break after a short amount of time in the case of 60 °C and 20 MPa test conditions. This time is much longer compared to PLA, ABS, and TPLA samples. This shows that the creep strength of CPE samples is higher than PLA, ABS, and TPLA.

The creep test results of PC test samples for different ambient temperature and loading conditions are illustrated in Fig. 6. According to the results obtained from the creep tests, it has been determined that the creep strength of PC material is very high compared to all other materials. In addition, the test samples produced from PC are the least affected by temperature and loading conditions. No damage occurred in the samples produced from PC material under this study's applied loading and temperature conditions. For this reason, PC materials should be used in parts that will operate under high temperature and high constant static loading conditions since creep is very low.

The creep test results for the nylon samples are seen in Fig. 7. The first and second creep stages are clearly seen for the nylon test specimens. Because, the maximum creep values are seen for the nylon test samples. The flexibility of the nylon is much higher than the other materials. However, no damage is seen for this material, even in the case of 60 °C and 20 MPa test conditions. The experiment was terminated because it went out of the measuring range of the micrometer. Parts produced from nylon with a 3D printer should be used in low loading and temperature conditions where flexibility is at the forefront.

The comparison of the creep test results of the five different materials under 10 MPa stress levels and different ambient temperatures is shown in Fig. 8. The first and second stage of the creep is seen clearly from the figures; also, the tertiary (accelerated) creep phase is seen only in PLA and TPLA under 60 °C and 10 MPa test conditions. During the first stage of creep, the elongation rate is high. However, due to the strain

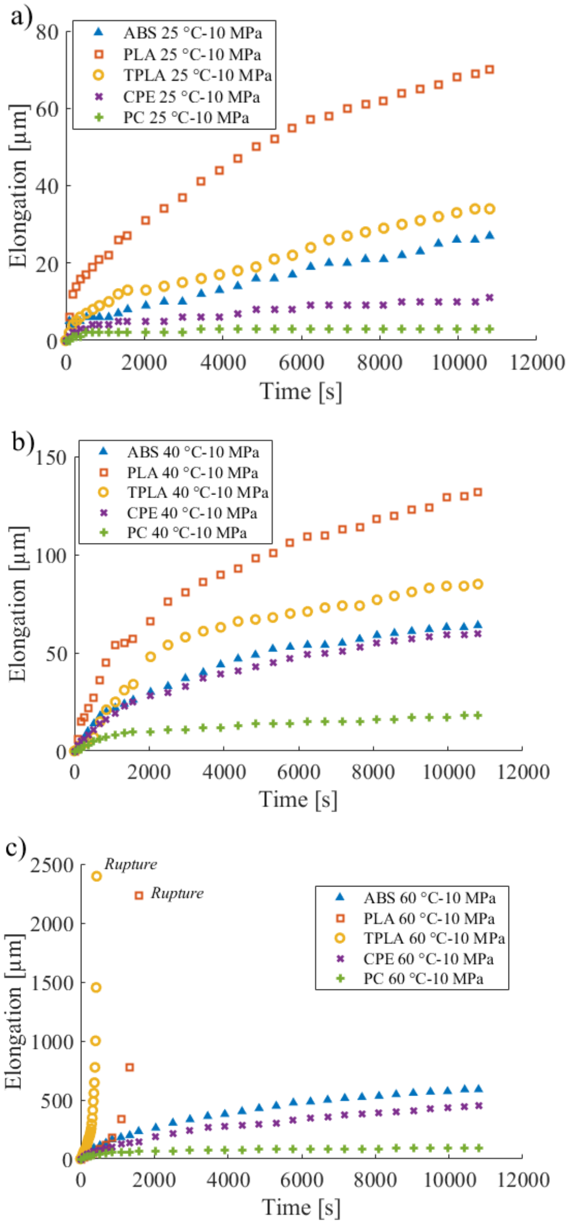


Fig. 8. *Comparison of creep test results of different materials under 10 MPa stress level and different ambient temperatures; a) 25 °C, b) 40 °C, and c) 60 °C*

hardening, the elongation rate slows down over time and reaches the lowest level, and remains constant. During the second stage of creep, the elongation increases approximately linearly with time. After the second stage creep zone, the elongation increases rapidly, and the specimens break. This region is called the creep region. The tertiary stage of creep is only seen for PLA and TPLA.

Fig. 9 shows the creep behaviour of samples produced from five different materials under 20 MPa loading and different temperatures. No rupture was observed in the experiments carried out at 25 °C and 40 °C ambient temperatures. However, in the experiments carried out at an ambient temperature of 60 °C, all other materials, except PC material, break quickly after a certain period of time. The amount of creep increases with the increase of the stress value from 10 MPa to 20 MPa. This increase in the amount of creep increases more with increasing temperature. Similar results are found in [14] to [20]. In addition, the increase in the maximum creep value increases with the increase in the stress level. Therefore, it cannot be said that there is a direct linear relationship between stress level and creep.

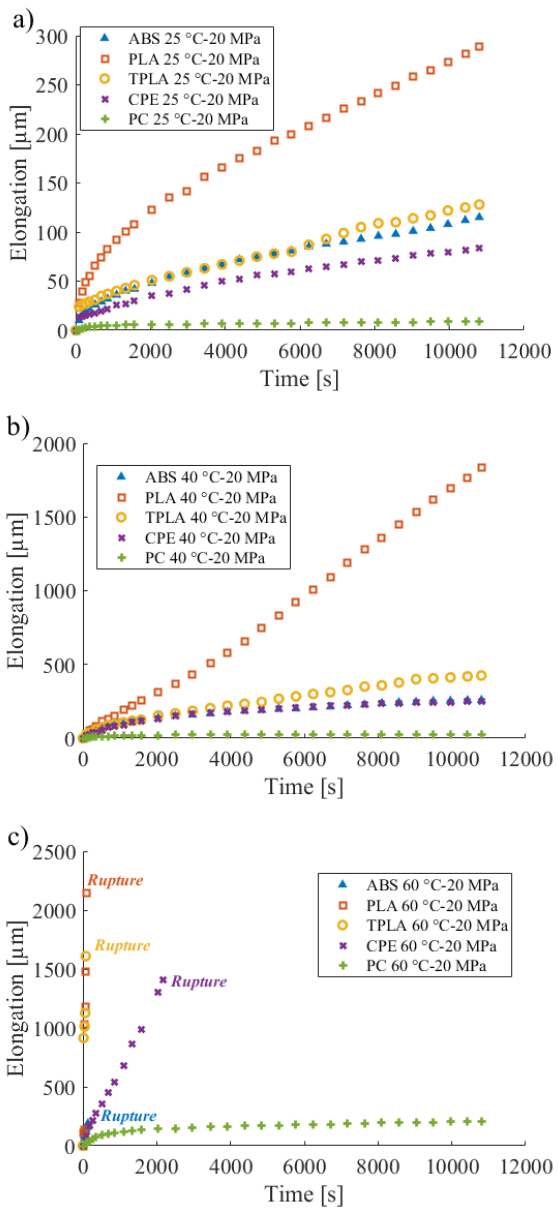


Fig. 9. *Comparison of creep test results of different materials under 20 MPa stress level and different ambient temperatures; a) 25 °C, b) 40 °C, and c) 60 °C*

3 CONCLUSIONS

In this study, the creep behaviour of test specimens produced from six different materials (PLA, ABS, TPLA, CPE, nylon, PC) by the additive manufacturing method was investigated experimentally under three different temperatures (25 °C, 40 °C, and 60 °C) and two different stress values (10 MPa, and 20 MPa). The creep test samples are produced by using Ultimaker 2+ Extended 3D printer and CNC milling to obtain a homogeneous structure. Creep experiments were carried out for three hours. The results of the creep tests performed in this study can be summarized as follows.

- The creep rate increases with the increase in ambient temperature and stress level for all materials used in this study.
- According to the test results, the load is a more effective parameter on creep than the temperature.
- PLA, which is the most commonly used polymer in 3D printers, is determined as the material with the worst creep resistance. For this reason, it is recommended that the parts produced using PLA with a 3D printer should be used at room temperature with no load or under very low static loads.
- Although TPLA has slightly better creep behaviour than PLA, it is not suitable for high temperatures and loads.
- According to the results obtained from ABS and CPE samples, these materials can be used at medium loads and moderate temperatures, but they are not suitable for use at high loads and temperatures.
- Although more creep occurred in the test specimens made of nylon compared to other materials, no rupture was observed.

- PC is determined to be the most resistant material against creep. The lowest creep amounts are observed in PC material in all experimental scenarios. Therefore, PC material can be used more safely than other materials under high load and temperature conditions.

After this study, the creep behaviour of polymer materials produced with 3D printers can be better understood by examining the effect of 3D printer production parameters (printing angle, nozzle diameter, layer thickness, extrusion temperature, printing speed, etc.) on creep under different temperature and loading conditions.

4 ACKNOWLEDGEMENTS

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