HDPE AND PVC CREEP AND THERMAL RATCHETING BEHAVIOR UNDER COMPRESSION

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ABSTRACT

This paper highlights the thermal ratcheting behavior of High Density PolyEthylene (HDPE) and Poly Vinyl Chloride (PVC) materials under uniaxial compression loading. The study investigates the influence of thermal cycling under compression of polymeric materials deployed in bolted flange connections. HPDE and PVC are two of the highly exploited materials for use in plastic piping systems and chemical industries. Exceptional corrosion and chemical resistance, frictionless flow and excellent service life make them the best alternative for conventional metal pipes in natural gas applications and domestic piping services. The research brings new insights on the effect of creep and thermal ratcheting on the mechanical behavior of HPDE and PVC. The cumulative deformation of these materials under combined influence of compressive load and thermal cycling is not implemented on the existing design standards. The need of the hour to accommodate thermal ratcheting behavior in the design of pressure vessel and piping components of polymers and thereby avoiding structural and leakage failure subjected to load and temperature variation.

1 INTRODUCTION

In today's modern world, the application of plastic materials has swept over conventional metallic design structure mainly for their extremely affordable cost and lesser depletion of natural resources. The other factors that widens the range of employment of polymer materials are their extensive protection against chemical and corrosion attacks, greater service life, light weight and relatively environmental friendly. Among the variety of polymeric materials commercially available, PVC and HDPE polymers have the highest percentage of industrial utilization as a fact their inherent chemical and mechanical properties that are suitable for a diversity of environmental conditions. Humongous amount of research has been carried out on characterizing the material properties and their response to particular type of deployment, as these materials are been around several decades, now. Some researches have focused on the creep behavior of ployermic materials as this phenomenon is increasingly being touted as a hindrance and drawback for these materials. Creep and stress rupture under various conditions of applied static stress and time is studied by Faupel [1] while the perennial properties of two varieties of PVC and polyethylene under liquid pressure at different temperature have been analysed by Niklas and Eifflaender [2]. Bergen has studied the thermoplastic creep behavior at temperatures close to the glass transition region of polymers [3].

The viscoelastic creep response of high density polyethylene is explored in two parts by Zhang and Moore [4,5]. This work developed two creep models, a viscoplastic model and a nonlinear viscoelastic model which fitted with experimental data has near perfect and moderate accuracy, respectively. The developed nonlinear creep model of high density polyethylene by Lai and Bakker [6] has a good agreement with the data from physical samples with the consideration of ageing and long term creep behavior. Colak and Dusunceli [7] have probed into the viscoelastic and viscoplastic behavior of HPDE under cyclic loading conditions. In addition, the microscopic and chemical structural analysis of polyethylene polymers under creep damage is done by Hamouda et al [8].

The existing literature on polymer materials is narrowly focused on the creep and ratcheting behavior of these materials under tension conducted on pressurized tubes [8,9,10,11]. Only few limited literatures on the mechanical ratcheting or fatigue can be found. Vinogradov and Schumacher [12] have examined the influence of cyclic loading rates under different temperature conditions on the cyclic creep behavior of polymers and polymer composites. Krishnaswamy [13] looked into the brittle and ductile failure under creep rupture testing of high density polyethylene pipes while Wham et al [14] analysed the horizontal ground strain capacity of PVCO pipes. There are no typical references available on the literature on creep data on polymeric materials under compression for use in applications such creep analysis of bolted flange joints subjected to compression. In bolted flange gasketed connections, the gasket is the component to blame for relaxation and very seldom the flange material itself [15]. However, in the case of polymeric flanges, a quintessential analysis of compressive creep behavior for different polymer is a necessity to insure their long term behavior.

In addition, unlike conventional metallic materials, lager scale of polymer materials has limited operating temperature conditions thereby making them vulnerable to temperature fluctuations. Consequence of thermal ratcheting or cycling of temperature on polymers is a relatively rare phenomenon in reported literature. The work by Bouzid and Benabdullah [16] on the hot blowout testing procedure for PolyTetraFluoroEthylene (PTFE) based gaskets is few of the scares research on the thermal ratcheting behavior of polymers.

From the extensive literature search, the cynosure of this research is on the coupled behavior of thermal ratcheting and compressive creep on the cumulative deformation of selected polymer materials (PVC and HDPE) under different temperature and stress conditions. The emphasis of this ongoing research is to incorporate compressive creep and thermal ratcheting response of polymeric materials used in the design of bolted flange joints.

2 EXPERIMENTAL SETUP

The intertwined compressive creep and thermal ratcheting analysis of HDPE and PVC polymer materials are preformed using the Universal Gasket Rig (UGR), a home built innovative experimental test bench shown in Fig. 1. The capability of UGR to characterize intricate mechanical and leakage properties of polymers is its greatest benefit. The UGR works under simple compression load implemented through a use of hydraulic pump and two platens. The applied compressive load on the specimens between the upper and lower platens is transmitted via a central stud which is screwed to the hydraulic tensioner head. The hydraulic system is provided with an accumulator in order to maintain pressure in the system and facilitate for the creep analysis under constant load. The platens can accommodate a hollow circular specimen with a minimum and maximum diameter of 50 inch and 100 mm, respectively. The maximum allowable thickness of the sample is limited to 5 mm. The test rig enables for combined application of internal pressure, thermal and uniaxial mechanical load on the test piece. This features provides for complex and tangled analysis of material properties under the above mentioned conditions. The UGR system can operate at a maximum internal pressure of 5 MPa on a controller high temperature environment of 450 °C.

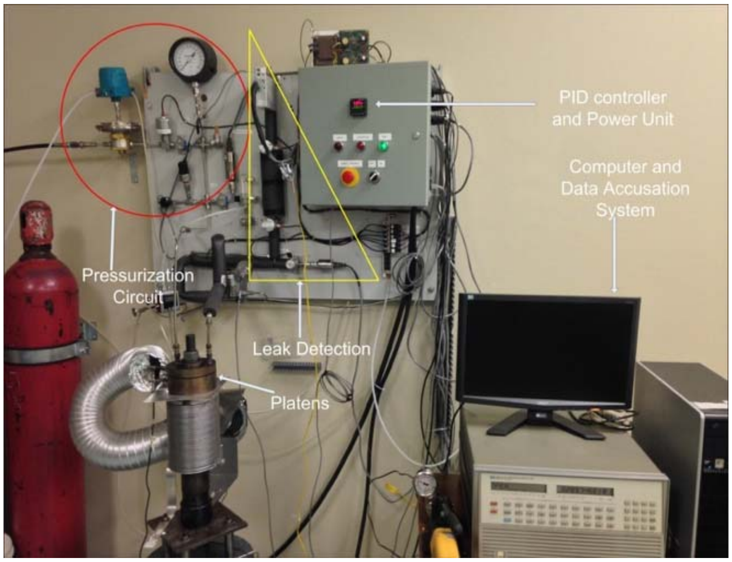

Figure 1: Universal Gasket Rig

The compressive creep response of sampling is monitored through high sensitive Linearly Variable Differential Transformer (LVDT). The implementation of heat to the sample is accomplished through an external electric ceramic band heater which is wrapped around the platens and most of the heat is transferred in form of conduction. The temperature of the heater is controlled by means of feedback loop connected to a Proportional Integral Differentiator (PID) controller as illustrated in Fig. (2.a). All the sensors, pertaining to load, temperature, displacement and leak are connected to a computer by means of an Data Acquisition and Control system (DAC). An emergency stop button along with temperature display and on/off buttons are provide with the electrical power panel.

Figure 2: (a) Heating System - right, (b) Specimen sample – left,

The heating is performed at a rate of 1.5^{o}C/min while the cooling is accomplished through natural convection. The process tries to replicate the industrial application of large section of bolted flange joints. The prevention of loss of heat to the environment is obtained by special insulation cover made of fiber materials and a stainless steel cap. The load applied on the specimen is measure through a Wheatstone bridge circuit (strain gauge) bounded at the bottom of the central stud. The apparatus can perform at maximum load of 70 MPa on a 645.16 mm^2 material sample. Additional key feature of UGR is the capacity to implement temperature cycles in order to study the thermal ratcheting response of the material tested. With the PID controller and LabVIEW program, the range of temperature and number of cycles along with time period for hold-off at a temperature can be provided.

3 TEST PROCEDURE AND MATERIAL SPECIFICATIONS

The sophistication of UGR makes it facile to achieve the characterization of polymeric materials. Typically, the commencement of test begins with manual measurement of polymer dimensions (Fig. 2.b) which are feed as inputs in the LabVIEW program to calculate the magnitude of stress applied through the compressive stress measurement by full bridge strain gauges. The system requires initial hand tightening of the nut to hold the two platens in contact with ring specimen before the application of load through hydraulic pump. This preliminary set position is defined as the zero position for LVDT sensor. Afterwards, the preferred magnitude of load is applied to the polymer specimen before or after the application of heat as necessitated by the type of test preformed. The rate of heating by the ceramic band electrical heat is set at 1.5^{o}C/min to be consistent with typical industrial fluid process heating rates. The data obtained from all the sensors are monitored in real-time using the custom built program that runs under LabVIEW platform. The measurements are monitored every ten seconds for control purposes while the values are recorded every 1 to 10 minutes as per the material response with time. The characterization tests of HDPE and PVC polymers are performed in two stages. The first one is the short-term compressive creep test the involves creep analysis of both materials for 4 to 5 days under different stress and temperature conditions. The second test is the thermal ratcheting evaluation which encompasses 20 thermal cycles between target and ambient temperature after 1 or 0 day of creep. The detailed elaboration of tests performed is provided in table 1 and 2. The dimension of the test specimens are standardised to 90 mm as outer diameter and 72 mm as inner diameter along with a thickness of 6.35 mm.

Table 1. Creep test parameters

High Density PolyEthylene & PVC			
Test #	**Temperature (°C)**	**Stress (MPa)**	**Time Period of test**
# 1	23	7, 14 & 21	5 days
# 2	50	7 & 14	5 days
# 3	60	7 & 14	5 days
# 4	70	7, 14 & 21	5 days
# 5	45	20 & 30	5 days

Table 2. Thermal Ratcheting test conditions

Test #	**Applied Stress (MPa)**	**Creep Temp (°C)**	**Ratcheting Temp (°C)**	**Days of creep + # of thermal cycles**
High Density Polyethylene				
T1	14	23	28 - 55	1 + 20
T2	7	23	28 - 55	1 + 20
T3	14	-	28 - 55	0 + 20
PolyVinyl Chloride				
T5	21	23	28 - 55	1 + 20
T6	27	23	28 - 55	1 + 20

4 RESULTS AND DISCUSSION

Most polymer materials are vulnerable to creep and temperature variations, high density polyethylene and polyvinyl chloride are not an exception. Furthermore, unlike metallic materials, polymers exhibit difference in creep strain under tensile and compressive load. Hence, a proper characterisation of compressive creep together with a good assessment of thermal ratcheting of HDPE and PVC materials is the need of the hour. The creep analysis of HDPE and PVC under different stresses and temperatures shows the materials susceptibility to both of loading. As shown in Fig. 3.a & 3.c, with an increase in magnitude of the applied compressive stress there is an increase in the amount of creep strain induced on the specimen over time. It can be seen that under different loads the specimen demonstrates different time periods to reach secondary creep stage, however, HDPE samples tested at different conditions reveals secondary creep within the first couple of days of test. At room temperature, HDPE creep strain has a growth of six and four times the consequently lesser stress, between 7 and 14 MPa and between 14 and 21 MPa, respectively. Similarly, on varying the temperature of the sample at same load (Fig. 3.b), the creep strain tends to rise with the rise in temperature. On an average, the magnitude of creep strain grows by 20 percent with every 10 °C escalation of temperature.

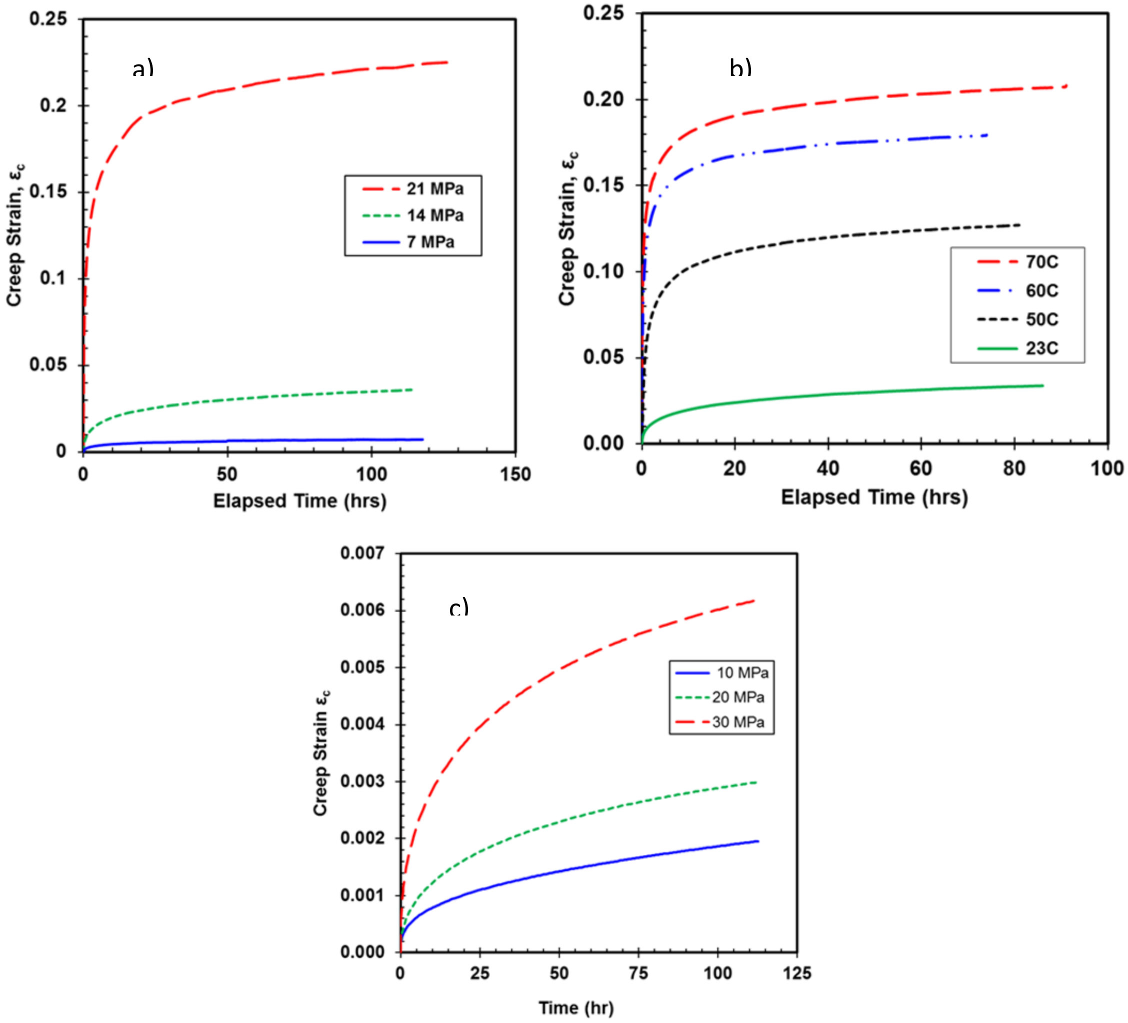

Figure 3: Creep strain (a) HDPE under different loads at room temperature, (b) HPDE under 14 MPa at different temperature, (b) PVC under different loads at 45 °C.

Another important characteristic property of HDPE is the creep modulus. The creep modulus is the instantaneous elastic modulus of the material that varies with time. The creep modulus is determined by calculating creep stress over creep strain. Fig. 4.a & 4.c illustrate the drop of creep modulus over time under different stress levels for HDPE and PVC, respectively. There is a significant drop in the creep modulus initially followed by a gradual saturation over time. The drop of creep modulus is quite rapid for test preformed at 21 MPa of stress while the decrease is not so intensive with 14 and 7 MPa of stress passing 10 and 30 hours respectively. The variation in the creep modulus of HDPE material at an applied stress of 14 MPa under specifically chosen temperature is presented in Fig. 4.b. There is humongous difference in the reduction of creep modulus between the room temperature and the high temperature tests. Moreover, the specimens tested at high temperature exhibit saturation of creep modulus reduction while the ambient temperature specimen does not saturate over the tested time period. The creep modulus dropped by 8 times the initial value in the first few hours of compressive creep test for HDPE at 70 °C.

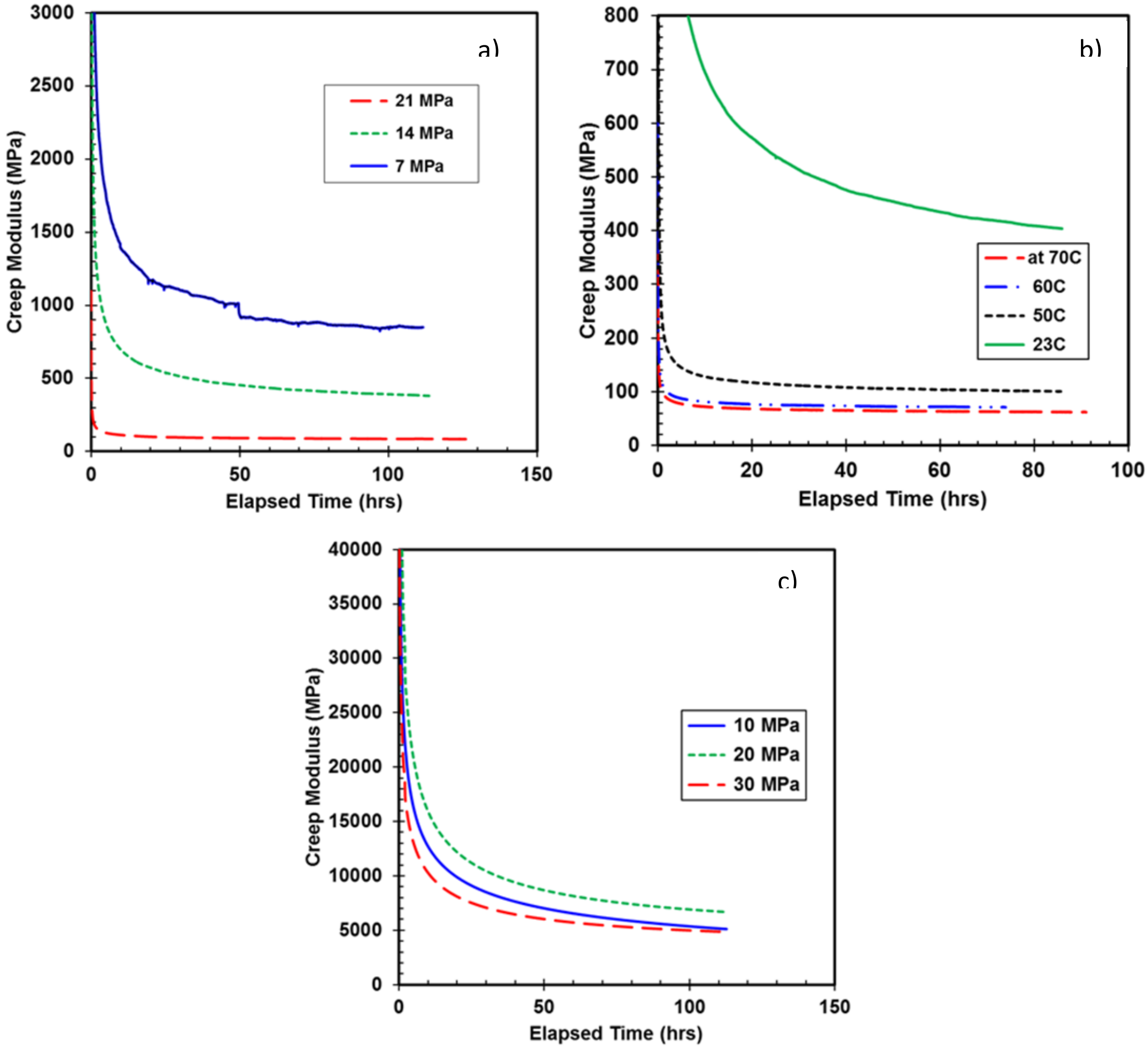

Figure 4: Creep modulus of a) HPDE under different loads at room temperature, b) HDPE under 14 MPa at different temperature, c) PVC under different loads at 45 °C

The thermal ratcheting or the thermal cycling behavior of polymer material is of utmost importance primarily due to the inherent property of relatively low glass transition temperature. Since a good selection of polymer materials can operate only in a moderate temperature conditions, a small perturbation in temperature can cause noteworthy change in the physical dimensions of the structures. Thermal cycling produces cumulative deformation that is harmful for structures made of high density polyethylene and polyvinyl chloride materials which usually operates below 60 °C. The cyclic fluctuation of temperature is applied to the test sample to understand the thermal ratcheting phenomenon.

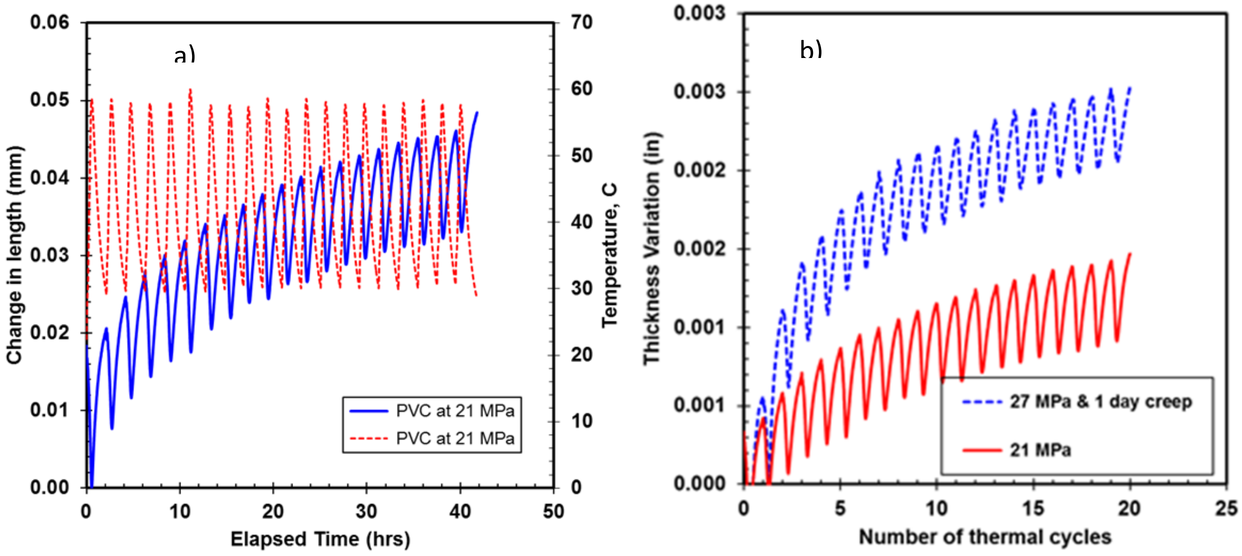

Figure 5: Change in length under thermal ratcheting of a) PVC with 1 day creep at 21 MPa, b) HDPE with and without 1 day creep at 14 MPa

In general, the thermal ratcheting tests of HDPE and PVC samples exhibit a cyclic escalation and reduction of length under compression with cyclic increase and decrease of temperature. This increase and decrease of axial thickness with each cycle is due to the expansion and contraction which can be visualised from the wavy nature of the graph as seen in figures 5.a & 5.b. However, there is net decrease in thickness of both materials with number of thermal cycles under compression. The effect of thermal ratcheting is more significant with HDPE than with PVC, nevertheless, both material did not display saturation of the cumulative damage incurred due to thermal cycles. The assessment of the influence of creep on thermal ratcheting of HDPE material at 14 MPa of stress is illustrated in Fig. 5.b. It is worth noting that the coupled interaction of creep and thermal ratcheting amplifies the damage incurred in the material in contrast to a specimen subjected to thermal cycling without creep. The initial exposure to creep has caused an increased reduction in thickness by 5 folds.

The significance of thermal ratcheting can be visualised with the thermal ratcheting strain which increase with each cycle of temperature fluctuations. The temperature cycling causes a gradual increase in thermal ratcheting strain of both materials under compression. Fig. 6.a presents the thermal ratcheting strain of PVC material at different applied stress levels. The magnitude of applied stress has a major influence on the overall amount of thermal ratcheting strain of the specimen under thermal cycling. With 7 MPa of increase in stress the PVC material displayed an almost 11-fold decrease in the thermal ratcheting strain at the end of 20 controlled thermal cycles. On comparing the ratcheting effect between HDPE and PVC (Fig. 6.b), the vulnerability of HDPE is highly exposed. While the PVC material exhibits a high thermal ratcheting strain, the HDPE exhibits nearly 15 times more reduction to the total thickness under same thermal ratcheting test conditions. It is noteworthy to mention; the HDPE has low thermal ratcheting strain than PVC even at relatively lower applied stress.

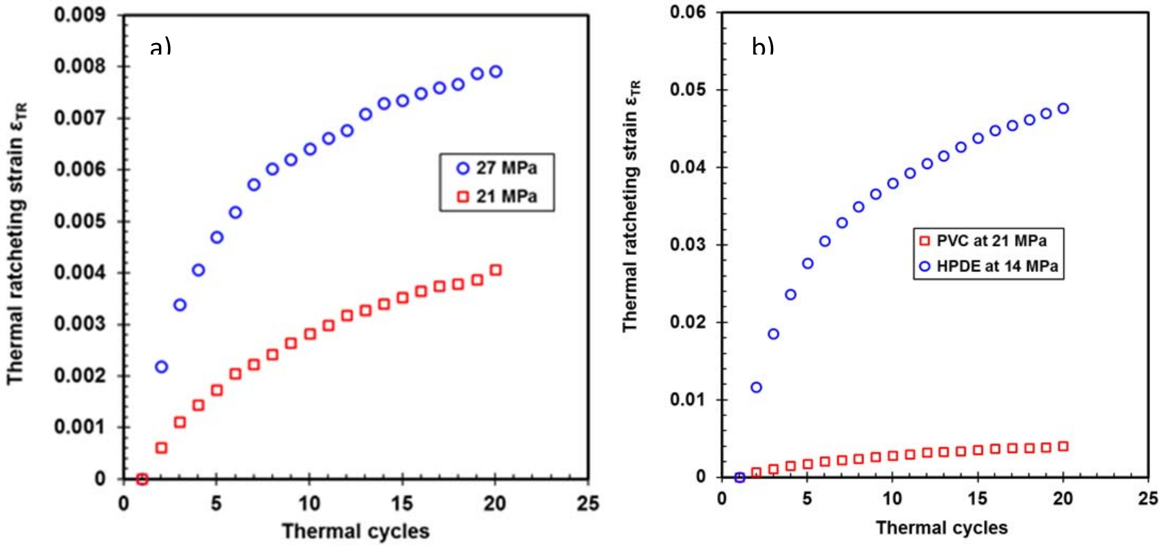

Figure 6: Thermal ratcheting strain of a) PVC at different loads, b) HDPE and PVC at different loads

Fig.7 shows a similar trend of decrease of thermal ratcheting strain of the HDDE with amplification of applied stress as with PVC material. Further to remarks could be made on the influence of coupled creep and thermal ratcheting; the thermal ratcheting strain is higher for the sample tested without 1 day of creep while the magnitude of total strain is greater for the sample tested with 1 day of creep at same thermal ratcheting temperatures. The possible reason for such behavior can be attributed to the induced strain due to creep triggering a diminution on the effect of thermal ratcheting. Nonetheless, the cumulative damage due to thermal cyclic is significant with only as little as 0.4% of difference in thermal ratcheting strain between the two test conditions.

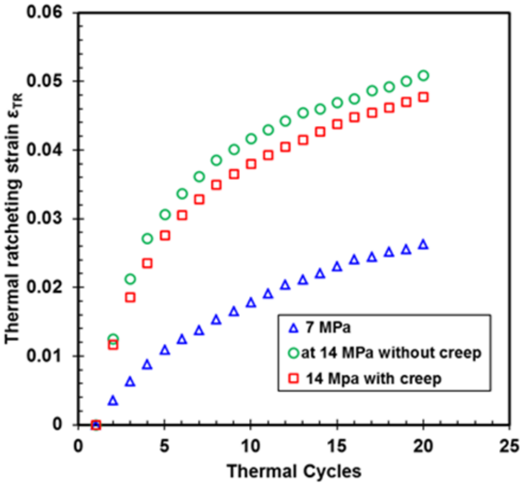

Figure 7: Thermal ratcheting strain of HDPE at different loads with and without 1 day creep

5 CONCLUSION

The characterisation test of chosen polymeric materials (HDPE and PVC) is successfully scrutinised by the use of Universal Gasket Rig. The plastic materials exhibit substantial creep and thermal ratcheting under different compressive loads and cyclic temperature conditions. In addition, both the specimens demonstrated thinning of thickness under thermal ratcheting with the magnitude of cumulative damage incurred is extremely influenced by applied stress and temperature. Overall, HDPE material exhibited higher susceptibility to compressive creep and thermal ratcheting in contrast to the PVC sample. The intensity of damage incurred varied by great extent between HDPE and PVC, rising the question on considering common design criteria for all polymeric materials. Finally, the implementation of compressive creep and thermal ratcheting behavior of polymer or plastic materials in design standard is a mandate.

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