Deformation and fracture behaviour of extruded CPVC sheet and pipe after exposure to chemical solvents

by

HANLIN MI

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering
University of Alberta

Abstract

The work described in this thesis concerns the influence of chemical solvents (acetone and primer) on the strength and ductility of extruded chlorinated polyvinyl chloride (CPVC) sheet with a nominal thickness of 1/32-inch, and of pipe that is 2-inch in diameter. The work also includes finite element (FE) simulations of tensile tests of CPVC dog-bone specimens with and without immersion in acetone or primer.

Dog-bone specimens from CPVC sheet and ring specimens from CPVC pipe were prepared for mechanical testing. Test results revealed opposite trends of change in ductility for these two types of specimens after exposure to chemical liquids. The ductility of dog-bone specimens increased after immersion in chemical liquids, whereas the ring specimens showed a ductility decrease under similar conditions.

Upon local exposure of the inner surface of ring specimens to chemical liquids, ductility of the specimens also decreases. Post-test examination on specimens with local exposure on the inner surface showed cracks around the area that had been exposed to chemical liquids, suggesting that such exposure encourages crack initiation, resulting in early fracture. Based on experimental observation, ductility reduction is caused by early formation of cracks in the surface region that was exposed to chemical liquids, which introduces stress concentration leading to premature fracture.

FE simulation of the mechanical behavior of CPVC dog-bone specimens in tension was used to establish the constitutive equations for linear and nonlinear deformation, neck initiation and strain hardening. FE models based on a one-quarter size specimen used in experimental testing were built using ABAQUS 6.12, with material input based on a table

of more than 1500 points, to closely mimic the experimentally determined force versus stroke curves.

This thesis concludes that exposure to acetone and primer weakened the mechanical properties of extruded CPVC sheet and pipe, but generated a different effect on ductility, i.e., causing a ductility increase for sheet specimens, but a permanent ductility loss for pipe specimens. It is believed that early fracture of CPVC pipe was caused by contact with acetone and primer on the inner surface, which led to early yielding in the solvent-affected-zone (SAZ) and resulted in stress concentration and crack generation. Therefore, solvents or detergent-based liquids should be carefully handled to avoid unnecessary contact with CPVC surfaces. Finally, it is suggested that the influence of chemical liquids on the ductility of CPVC material, especially in pipe forms, should be carefully characterized to ensure the reliability of the material in long-term service.

Preface

The purpose of this research is to entitle the Master of Science at the University of Alberta to 'HANLIN MI'. No part of this thesis has been published previously.

Acknowledgements

Table of Contents

Lists of Tables

Lists of Figures

xi

Lists of Symbols

S_f	Stroke value for the onset of fracture for specimens in test
σ	Nominal tensile strength of CPVC
F_t	Nominal tensile force to break CPVC sheet specimen
F_c	Nominal force to compress the CPVC sheet specimen
ASTM	American Society for Testing and Materials
CPVC	Chlorinated polyvinyl chloride
ESC	Environmental stress cracking
FE	Finite element
MEK	Methyl ethyl ketone
NPR	Notched pipe ring
PVC	Polyvinyl chloride
SAZ	Solvent-affected zone
SCG	Slow crack growth
SEM	Scanning electron microscopy
THF	Tetrahydrofuran
UV	Ultraviolet
wt%	Weight per cent (Mass fraction)

Chapter 1 Introduction

1.1 Background and motivation

The use of plastic pipe has multiplied since the mid-1940s, replacing metallic pipe for application such as gas and water transportation, waste drainage, and sewer distribution [1][2][3]. Plastic pipes are now widely accepted by the industry because they cost less than their metallic counterparts, and are easier to transport and install due to their lightweight [4][5]. Plastic pipes are also less noisy than copper pipes in service [6] and have fewer issues related to corrosion and condensation [4][6]. Among commercially available plastic pipes, polyvinyl chloride (PVC) pipe accounts for over 60% of the piping market [7][8][9]. Although PVC pipes have the benefits described above, they also have several shortcomings that could lead to catastrophic malfunctions [4]. Concerns about PVC pipes come from their brittle nature with low resistance to strike and abrasion [10], negative resistance to certain chemical liquids, such as some esters [11][12] and sensitivity to excessive heat or sunlight [13].

Chlorinated polyvinyl chloride (CPVC) pipe is a heat-resistant version of PVC pipe that has been commonly used for hot-water transportation in residential buildings due to the significantly higher glass transition temperature (T_g) than PVC [9][14][15]. CPVC pipe was first introduced to the commercial marker by Lubrizol Advanced Materials in 1959, to replace metallic pipe in hot-water distribution systems or in chemical plants for transportation of caustic liquids of high pH [16][17]. Production of CPVC is through a chlorination reaction in manufacturing. The ratio of the chlorine atom is increased from 25% in PVC to about 40% in CPVC [18]. This additional chlorine in CPVC improves resistance to corrosive chemicals [16].

To joint CPVC pipes in practise, one approach is called solvent bonding [19]. This strategy is increasingly significant in pipeline construction applications because it is relatively easy to handle, flexible and cost-efficient in service [20][21]. A representative of this strategy is the standard ASTM D2855 [22], two-step practice for manufacturing CPVC pipe joints that uses primer as a softener [23], and solvent cement as a gap filler [24].

Since chemical liquids is used in this approach, their effect on the properties of plastics in contact with needs to address. The intrinsic resistance of plastics to chemical liquids has been studied through solubility parameters, together with the structures of hydrogen bonding in plastics [25]. For plastic and chemical liquids that have a small difference in solubility parameters, the liquid is likely to promote cracking on the plastic, but if the difference is large, the liquid would often act as a crazing agent. When the solubility parameter is identical between the liquid and the plastic, the liquid can be a chemical solvent for the plastic [25].

Existing studies also tend to characterize of the resistance of plastics to chemical liquids based on (a) observation on states of crazing, cracking or dissolution on bent (pre-strained) plastic films while immersed in chemical liquids or (b) the calculated strain for geometric deformation of the specimens due to the immersion in chemical liquids [25][26]. Today, there are widely accepted standards to characterize the chemical resistance of plastics, such as ASTM D543 [27] and ISO 22088 [28].

ASTM D543 has two steps for characterization. The first step is related to physical appearance, which records the change in appearance and color of plastics after exposure to chemical liquids. The weight of the specimen before and after immersion is also measured, as well as the dimensions. The second step addresses mechanical properties, and aims to investigate mechanical property changes due to exposure to chemical liquids [27]. Tests are conducted to compare immersed specimens and non-immersed ones. The immersed specimens are also required to test immediately after removal from the chemical liquid or even while immersed [16]. A cooling operation is specified before mechanical tests if these specimens finished immersion in an elevated temperature environment. The tensile test is generally preferred for the study of mechanical property changes in plastics. Note that if the chemical liquids used are aqueous solutions, the control test should be conducted on specimens immersed in water as well [27].

ISO 22088 provides similar test processes to determine the chemical resistance of plastics. It provides two criteria to characterize the resistance performance of plastics, one being a gradually increasing load on the specimen until specimen fracture, and the other being the time duration for rupture of the specimens with a fixed load [16].

Standards covering the characterization for resistance of plastics to chemical liquids provide industry with guidelines to test CPVC for industrial use as a pipeline material, and the application of solvent-welding techniques in pipe structure. Most of these promote replacement of metallic pipe by CPVC pipe. However, leaking issues with CPVC pipe containing solvent-welded joints in industrial applications have attracted the author's interests [26][29][30][31], because this type of CPVC degradation cannot be explained by exposure to intense UV light along with high moisture or temperature [32][33]. More importantly, it seems to be opposite to the perceived benefits of plastics in resistance to chemical liquids.

1.2 Literature review on the fracture modes of CPVC pipe and the extrusion of CPVC in the form of sheet and pipe

The chemical resistance literature reveals that CPVC has the premium capability to resist most chemical liquids [25][26]. However, concerns have been raised about the performance of solvent-welded joints in CPVC pipelines, because the welded joints have been reported to be able to withstand loads up to 70% of the strength of the parent materials [34], and the strength of the primer-affected-zone in CPVC ring specimens was found to recover up to 63% of the strength of the virgin ring specimen [29]. More importantly, the ductility of the primer-affected pipe is also greatly reduced [29]. Primer is a mixture of solvents, including methyl ethyl ketone (MEK), acetone, cyclohexanone (CYH) and tetrahydrofuran (THF) [35]. From the safety data sheet of the primer, acetone accounts for the highest weight per cent (wt%), for example, acetone make up 25%-40% by weight in purple primer [36], and in the clear primer used in the current work, acetone constitutes up to 60% [37].

Even though the survey in 2012 reported that CPVC has the lowest break rate as a piping material [38], it is necessary to determine the common fracture mechanisms of CPVC pipe, which may provide insights into the role of primer in the rupture of primer-contacted CPVC pipe.

The fracture modes relevant to CPCV pipe have been categorized as softening, degradation, erosion and cracking [39]. Softening is a typical fracture mode that is characterized by the presence of swelling or distortion that usually leads to a failure by ballooning or ductile ruptures. The reasons for softening are mainly material absorption of chemical solvents from the surroundings or exposure to an environment exceeding the recommended temperature or pressure. Among the chemical solvents (or plasticizers) that soften CPVC, the ketone family is typical, with the simplest form being acetone. Degradation occurs when materials are exposed to an environment with high temperature or to chemical liquids that destroy the vinyl resin or other ingredients in the polymer. Hot concentrated sulfuric or nitric acid may cause different degradations such as blackening and blistering, or whitening and surface etching. These acids were not used in this work, and therefore the related degradation is not discussed here. Erosion of polymers may come from an invasion of solid particles, or from fluids streaming on surfaces and causing degradation and embrittlement. Again, no such scenario is relevant to this work. Cracking of CPVC has been significantly discussed from the viewpoint of environmental stress cracking (ESC), which appears when polymers are exposed to chemical liquids that are weak solvents or non-solvents. These liquids may generate noticeable property losses in polymers, which is suspected to be caused by surface wetting and weak capability to penetrate deeper into the polymer leading to a localized low-tension region that encourages crack development.

In addition, early fractures may occur due to pipe manufacture, design or installation of the pipeline. For example, a sewer pipeline failed to work after only 34 years, although it was designed for long-term service over 100 years [40][41]. Visual and micro-scale examination of broken samples proved that the pipe failure had no relation to contact with drain waste, but was rather due to the manufactured (inherent) flaws in the pipe wall and possible stress concentration (risers) originating from pipeline design and installation [42].

The CPVC specimens in the current work were manufactured by one of the common approaches widely accepted in the industry, (hot-melted) extrusion (HME). Extrusion is flexible and straightforward to changeover for running versatile manufacturing missions

[43][44]. In extrusion, a mixed plastic compound is melted and progressively pushed forward inside a heated barrel, which is usually realized by operation of a spiral-shaped screw or screw set mounted in the barrel. The molten plastic is conveyed to a die that generates the desired shape of the items, such as sheets or films, tubes, and frames then passed to impart a surface finish, and finally trimmed to design dimensions [45][46]. The properties of polymer flow are critical to the quality of the final products [43]. Improvements to extrusion process quality include adjusting the length-to-diameter ratio of the barrel for efficient heating, use granular feedstock and selection of a beneficial screw speed [47][48]. Study of the failure mechanism of premature CPVC fracture may be affected if the specimens tested were processed by different manufacturers.

1.3 Objectives and outline of the thesis

This work does not touch on the effect of manufacturing on the mechanical properties of CPVC specimens from either extruded sheet or extruded pipe. The potential fluctuations of test results were possibly due to the influence of manufacturing, i.e., extrusion, and efforts were made to minimize them by ensuring the consistency of raw material coming from the same manufacturer and the same batch. The diffusion rate difference within amorphous material as contact with chemical liquid, as described in the work of Titow *et al*. [49], has not discussed as well, with the assumption that the region of specimen exposure to chemical liquid is uniformly diffused.

The author's interests in this study come from the affinity of acetone to CPVC [29], because acetone accounts for the largest weight fraction in primer [36][37], and previous studies have simply indicated acetone as the simplest form of ketone that may soften CPVC pipe [16]. One of the goals of this work is to follow ASTM D543 [27] to determine the effect of acetone on the mechanical properties of CPVC sheets. The study includes an analysis of yield strength and initial slopes from the load-displacement curves of treated specimens.

The main objective of this study is to investigate the ductility change in CPVC specimens, in the form of extruded sheet and pipe, due to exposure to chemical liquids. Previous

studies focused on both notched and non-notched CPVC specimens in immersion to primer as a treatment and only in the form of extruded pipe, which concluded the early fracture of pipe specimens [29][50]. In this study, CPVC sheet specimens were used to compare the ductility change between sheet and pipe specimens after the specimens were treated with chemical liquids. In addition, possible reasons for the ductility decrease of chemical affected CPVC pipe [29] were explored by conducting experimental testing on CPVC ring specimens after exposure to chemical liquids on local areas..

The current work also uses a set of constitutive equations to simulate mechanical tests of CPVC sheet specimens with or without treatment by chemical liquids. Finite element (FE) simulations were conducted using ABAQUS 6.12. Yield stress-plastic strain relations were collected to compare the effects of different chemical liquids, i.e., acetone and primer on the elastic-plastic deformation of CPVC.

Chapter 2 illustrates the design history of in-house-built equipment to perform the tensile test for a CPVC sheet specimen while immersing in chemical liquid [51], and presents some design considerations and installation steps that are required by the ASTM D543 standard to be reported along with any experimental data [27].

Chapter 3 provides details of the preparation of CPVC specimens for immersion and tensile tests, as well as relevant results. It includes observation and measurements of physical changes in CPVC sheet specimens during and after immersion in acetone and tensile tests of CPVC sheet specimens, either during immersion in acetone or after acetone or primer treatment and drying for a certain time. In addition, the chapter includes D-split tests on CPVC ring specimens after immersion or local exposure to acetone or primer and drying for a certain time. It also provides an analysis of the results of the tensile tests from CPVC sheet and pipe specimens. It summarizes the influence of acetone application to CPVC sheet specimens on the test results and compares the difference in the ductility change for CPVC in the form of sheet and pipe specimens. Most importantly, the chapter provides an explanation for the decrease in ductility of pipe specimens after treatment in chemical liquids, but the increase in ductility of sheet specimens after the similar treatment.

6

Chapter 4 discusses the application of constitutive equations to simulate the tensile test results of CPVC virgin sheet specimens after treatment (acetone and primer), up to a point before the onset of fracture. It includes an introduction to the method adopted in the current work and a comparison of the change in the equivalent stress-strain relations of specimens after treatment using different chemical liquids.

Chapter 5 summarizes the findings of the current study and its potential limitations, as well as providing suggestions for relevant research areas that can be addressed in future work.

Chapter 2 Design process for in-house-built equipment and instructions for installation

To study the resistance of CPVC material to acetone, mechanical tests should be conducted on CPVC specimens that have been immersed in acetone for a while or that are still being immersed during the test [16]. The equipment has been designed in house and can be installed in the screw-driven universal test machine. Critical functions for the design include: (a) to provide the test specimen with an environment that contains chemical liquid, (b) to enable the tensile test to be conducted while the specimen is being immersed, and (c) to prevent massive evaporation of chemical liquid.

The first idea for the design was to fix the specimen by means of clamp arms, which were symmetrically designed as left and right subparts, as illustrated in Figure 2-1. The specimen is compressed by adjusting the position of the clamp arms and then finally tightening them together by the screw-and-nut structure on the side. Then the assembly is fixed to the test machine by hex screws through the slots as shown in Figure 2-1(c), which improves the degree of freedom (DOF) for the clamp arms to provide a suitable fixation position, and the container and the red cap are snapped to each other by screws. However, the design is difficult to continue, most importantly because of the insufficiency to realize tensile test for sheet specimen.

(a) (b) (c)
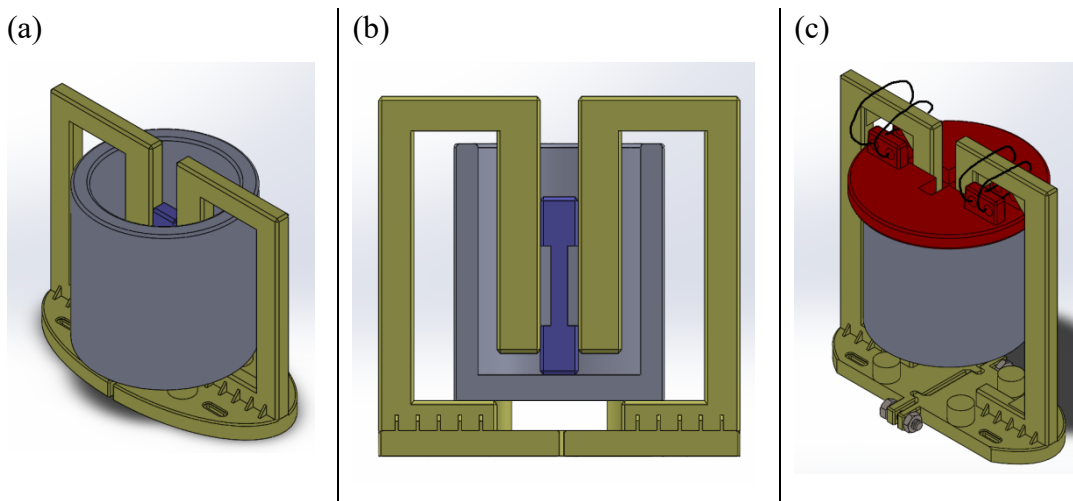
Figure 2-1 Schematic illustration of original idea for the fixture design.

The second design follows the principle that the equipment should be based on the conventional fixtures for the tensile test. In this design, a container encloses the bottom

part of the fixture, as shown in Figure 2-2(a), replaced later by a cylinder-shaped container, as shown in Figure 2-2(b).

(a)   (b)
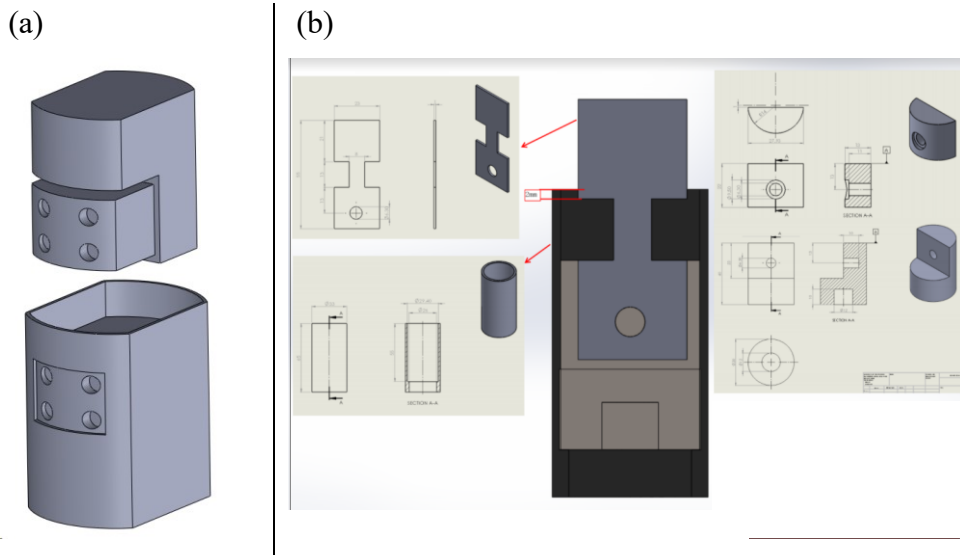
Figure 2-2 Schematic illustration of draft idea for the second fixture design.

To prevent evaporation of chemical liquid, the container was designed to be sealable from the top with a hollow lid having no friction with the fixture that would move upwards in the tensile test. The bottom seat was also introduced to stop the chemical liquid from escaping. This idea is presented in Figure 2-3.
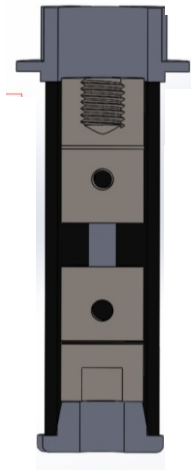
Figure 2-3 Schematic illustration of the final idea for the fixture design.

The foundation of the fixture was now established, and the following steps addressed the problem of leaking among fixtures, and simplified the cover structure.

Leaking could occur at two positions: the bottom edge of the container and the edges between the parts screwed to the bottom rod. Many plans were discussed, after which the decision was made to cut two grooves into the bottom seat as shown in Figure 2-4(a), where the grooves are used to house chemical-resistant O-rings. Sealing is provided through a thread fit to lock down the connecting parts and the compressed O-rings between them. The larger O-ring was compressed by assembling the bottom cap shown in Figure 2-4(b) and the container, as illustrated in Figure 2-4(c). To reach a seamless assembly, two blind holes were symmetrically drilled into the bottom cap, so that tools, rather than hands, could help fasten the assembly with high torque.

The small O-ring was squeezed as the bottom fixture was screwed to the bottom seat, and the seat was stopped by the hex nut, as illustrated in Figure 2-4(c). The sizes of O-ring used in this work were selected from the chart of standard USA O-ring sizes, given in the Appendix.

The top cover was simplified as a top cap. Half the top cap is in Figure 2-4(d), the other half has a shape symmetrical to the part shown. When assembled, the central cut-off region ensures that the tensile test is not affected by these caps.
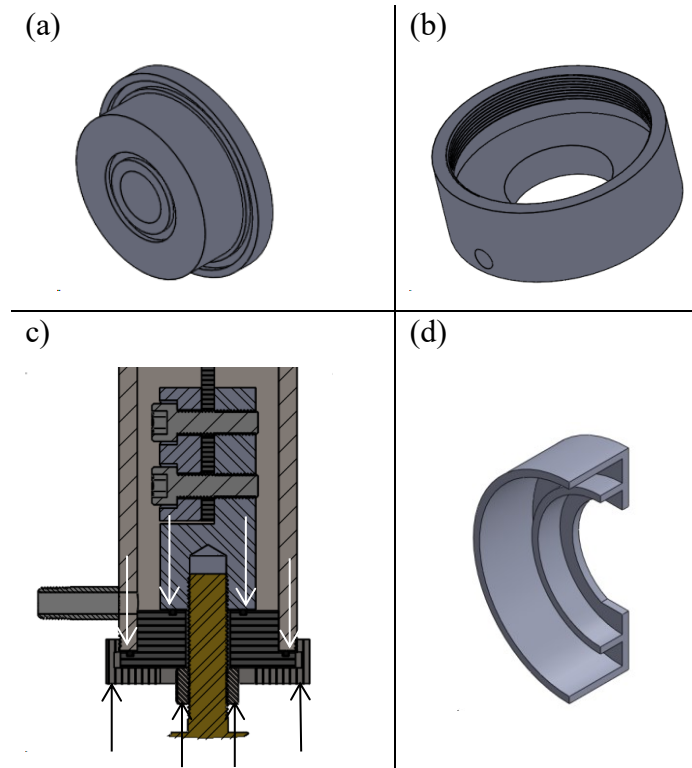
Figure 2-4 Schematic illustration of parts and sealing mechanism of the design.

To ensure that the fixtures could sustain the tensile force needed to break the specimen, calculations of the relevant force were carried out based on Eq. *2-1*, where the force (F_t) is estimated by multiplying the tensile strength of the commercial CPVC plate by the cross-sectional area of the specimen. The tensile strength σ was found to be 58MPa, and the cross-sectional area (a) can be obtained from Figure 3-5(a) as, $8\text{mm} \times \frac{1}{32} inch \approx 6.35 mm^2$.

$$\frac{F_t}{a} = \sigma \qquad (2\text{-}1)$$

The force needed then was estimated to be: 368.3N. Because the specimen is fastened to the fixtures by socket head screws, the contact region is assumed to be through friction with a static friction coefficient(µ) of 0.8. The least compression force (F_c) required is obtained by satisfying Eq. *2-2*:

$$\mu * F_c \geq F_t \qquad (2\text{-}2)$$

Considering the reasonably smooth surface of the specimen and fixture, it was decided to enlarge the clamping region of the specimen to create more contact area. Accordingly, the fixtures used to compress the specimen were also enlarged.

Given a safety factor of 2, there are four socket head screws that fix the specimen, each of which provides a tightening force of about 230 N. After referring to the machinery's handbook [52], the M18-8 stainless steel socket head screw was selected.

Figure 2-5 shows an exploded view of the final version of the entire fixture. A detailed explanation with name and part number is provided in the Appendix. The dimensions of the CPVC sheet specimen that matched the fixture described here are given in Figure 3-5 (a) of Chapter 3.
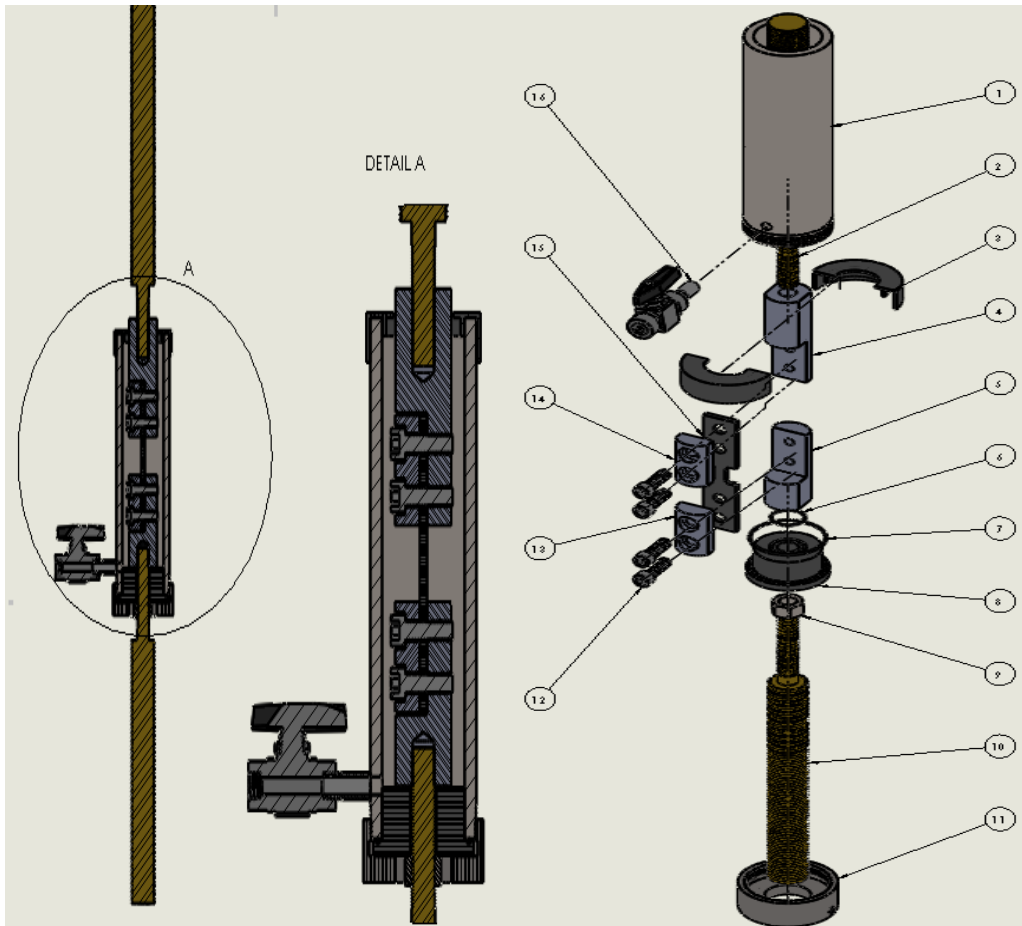
Figure 2-5 Schematic illustration of the finalized fixtures with a specimen thickness of 4 mm for presentation.

A standard threaded nipple pipe was welded to the stainless-steel tube. The standard threaded nipple pipe contains an ON/OFF ball valve at one end to control the outlet of chemical liquids.

As illustrated in Figure 2-5, the sequence to assemble the fixture is:

- Put the bottom cap through the bottom screw rod and screw the hex nut into the bottom screw rod.
- Assemble the bottom seat, screw the bottom fixture in the bottom screw rod, and fasten the rod to the test machine.
- Fix the test specimen to the bottom fixture.
- Put the stainless-steel container through the top fixture and hold it up to provide space to fix the test specimen to the top fixture.
- Turn and tighten the stainless-steel container to the bottom cap.
- Check that the ball valve is OFF, add chemical liquid into the chamber and cover the top cap before the test.

Chapter 3 Tensile test results on CPVC specimens of sheet and pipe

This chapter describes the experimental work conducted in this study. It also includes observation of physical deformation of CPVC strip specimens while immersing in acetone and recording weight change before and after immersion. Dimensions of CPVC dog-bone and ring specimens are presented, following the introduction of their treatments. The cross-section of ring specimens after treatment is illustrated in a schematic way, which is mainly to point out the location of the 'shell' region and 'core' region. Results from tensile tests are summarized into two parts, i.e., tensile tests for CPVC dog-bone specimens and D-split tests for CPVC ring specimens. For CPVC dog-bone specimen, the results are divided into two parts, i.e., 'wet' and 'dry' tests, where 'wet' test was conducted while the specimen had been immersed in acetone for a period and still being immersed in the test, but 'dry' test, on the other hand, was conducted after specimens had been immersed in chemical liquids for a period and dried for different periods in the air. In addition, it is a description of the tested CPVC specimens, and to ring specimens, there are also comparisons about the fractured cross-sectional area. Finally, there is analysis and discussion about the findings from the overall tests.

3.1 Preliminary test to investigate the effect of immersion in acetone on CPVC sheets

According to practice in ASTM D543 for immersion test [16], the purpose of the preliminary test is to observe the physical change of specimens and record the weight change after immersion for different time periods. Weight change of the CPVC strips is to quantify the amount of acetone absorbed into the specimen, and the weight change as a function of immersion time is used as a reference to select of the length of immersion time for the study about the effect of acetone on the mechanical property of CPVC sheet. A series of preliminary tests were conducted, using the 1/32" CPVC strips with a length of 55mm, and width of 8 or 16mm, as shown in Figure 3-1.
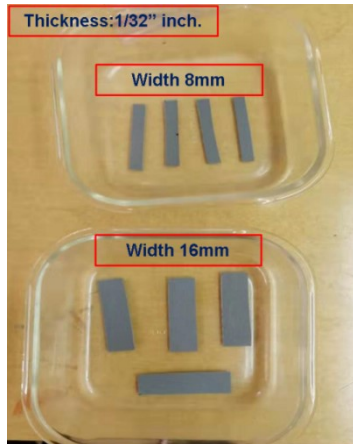
Immersion of specimens in acetone was carried out in the fume hood. Strips were very prone to stick to the bottom surface of the container after immersion for about 3 minutes. This should be avoided as it would generate different absorption rate between the top and bottom surfaces of the strips, i.e., slow down the absorption process from the bottom surface to warp the specimen. The warping affects the flatness of the specimen, which may be worsened during the following drying process, eventually affecting the tensile test results. Warping would be more evident as the width of the specimen increase and thickness decreases.

Therefore, the container was shaken periodically during the immersion process, and when specimens were found stuck to the bottom of the container, a razor blade was inserted between the specimen and the container surface to separate them. This process should be done with caution, and usually little insertion from an edge of the specimen would work.

In general, specimens were found to undergo four stages during the immersion:

    a) Immersion in less than 30 minutes: no obvious deformation appears.

    b) Immersion in around 36 minutes: a noticeable wrinkle appears.

    c) Immersion in over 39 minutes: specimens become flat again.

    d) Immersion in around 2 hours: corners of the specimen are dissolved.

Length of the immersion time in acetone was from 30 minutes to 42.5 hours. At the end of each immersion period, the specimen was carefully taken out of the container, with the residual acetone on the surface gently wiped off and then measured within a plastic bag

to avoid contaminating tray of the electronic balance. The weight of the empty plastic bag was also measured. Weight gain (%) for the specimen after immersion in acetone was calculated using Eq. *3-1*:

$$W_{gain\%} = \frac{W'_{total} - W_{total}}{W_{specimen}} \quad (g/g) \tag{3-1}$$

W_{total} is the weight (in gram) of the specimen before the immersion ($W_{specimen}$) and the plastic bag, W'_{total} weight of the specimen after the immersion and the same plastic bag.

Weight gain (%) is plotted as a function of logarithmic immersion time in minute. As shown in Figure 3-2, the weight gain for specimens of 8mm in width, immersed in acetone increased gradually to reach the value of 104.60% after the immersing for 2 hours, after which the weight gain remained relatively constant till the immersion time reached about 14 hours when weight increase started to drop. The drop of weight increase suggests that the CPVC material dissolved in acetone is more than the weight of acetone absorbed into the specimen. The nonlinear relation between weight gain of CPVC specimens and the immersion time reflects the acetone diffusion in dog-bone specimen does not remain as constant, which indicates the Fick's second law for diffusion may be applicable to build up the analytical model to the study of diffusion of acetone in CPVC material [53].
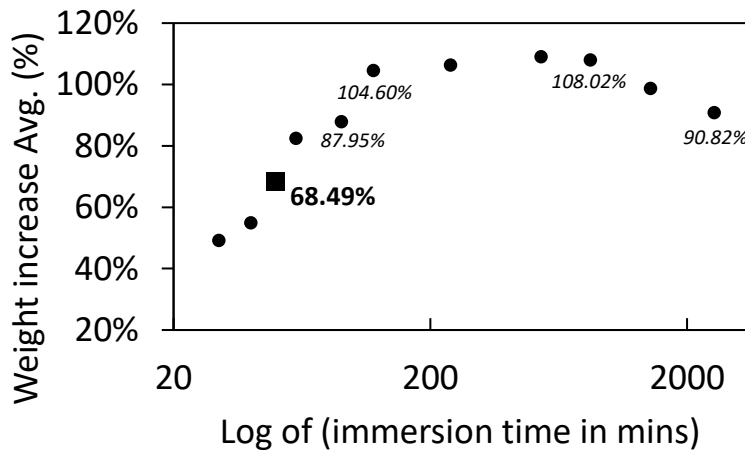
Figure 3-2 Weight increase v.s. Immersion time of 1/32" CPVC film in acetone with size of 8mm by 55mm.

Since CPVC strip specimen showed apparent dissolution in acetone after immersing for around 14 hours, the immersion process with equal or over 14 hours would not be considered for the immersion treatment.

The study investigated the effect of immersion in acetone for dog-bone specimens of three specific periods, 30, 40 and 55 minutes. Profile of CPVC dog-bone specimens used is discussed later, in Figure 3-5. In general, longer immersion time yields higher acetone absorption to the specimen, corresponding to a larger value for the weight gain. However, the weight increase of these specimens after drying for 6 hours in air shows inconsistency as plotted in Figure 3-3.

Figure 3-3 showed that the specimen with the longest immersion time of 55 minutes has the lowest value of weight gain among data within the three immersion periods selected for the study. The other two cases, i.e., immersed for 30 and 40 minutes, show consistent weight gain with only 0.1% difference. This indicates that immersing CPVC dog-bone specimens in acetone for 55 minutes is too long to avoid dissolution of CPVC in acetone.
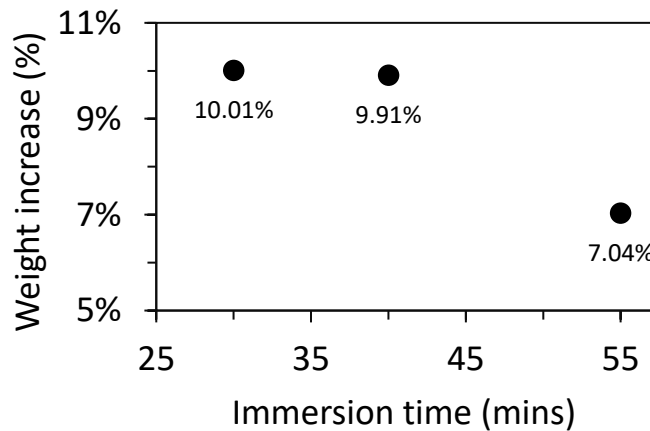
Figure 3-3 Weight increase of CPVC dog-bone specimen after different immersion time in acetone and drying for 6 hours.

A more remarkable presentation can be seen when combining values of weight gain for specimens right after immersion to those values after drying for 6 hours. It is shown in Figure 3-4 that weight increase of specimens right after immersion has nearly a linear increase with immersion time from 30 to 55 minutes, but, the 55-minute shows the lowest

weight increase after being dried for 6 hours. This might be caused by dissolution of CPVC in acetone or material loss during the handling.

Overall, there are risks to select immersion time equal to or over 55 minutes. Therefore, 40 minutes was selected as the immersion time to treat CPVC dog-bone specimens in acetone, as it provides the higher averaged value of weight increase, i.e., about 54.9%.
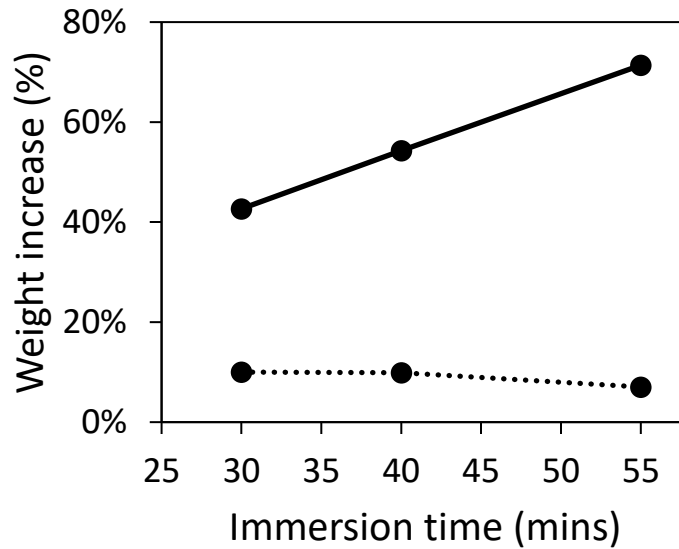
Figure 3-4 Comparison of weight increase for CPVC dog-bone specimens. 'Solid line' represents the weight gain of specimens after immersion. 'Dashed line' represents the weight increase of the specimens after drying for 6 hours.

CPVC dog-bone specimens were found to be very tacky after immersion in primer for 15 minutes and found to dissolve in primer after immersion longer than 15 minutes. Therefore, the immersion time of 10 minutes is selected to study the effect of immersion in the primer on the mechanical property change of the CPVC dog-bone specimen. The value of weight increase for CPVC dog-bone specimens after immersion in primer for 10 minutes was found to be around 25.1%.

3.2 Specimens dimensions and preparation

Dog-bone specimens were prepared from commercial CPVC 1/32" (12"×12") sheets through water-jet. Dimensions are presented in Figure 3-5(a). Ring specimens were prepared from commercial CPVC 4120 SCH80 2-inch (50mm) pipes. Dimensions are

shown in Figure 3-5(b), where the nominal width(w_0) was designed to be same as the wall thickness(t_0).

(a)

(b)
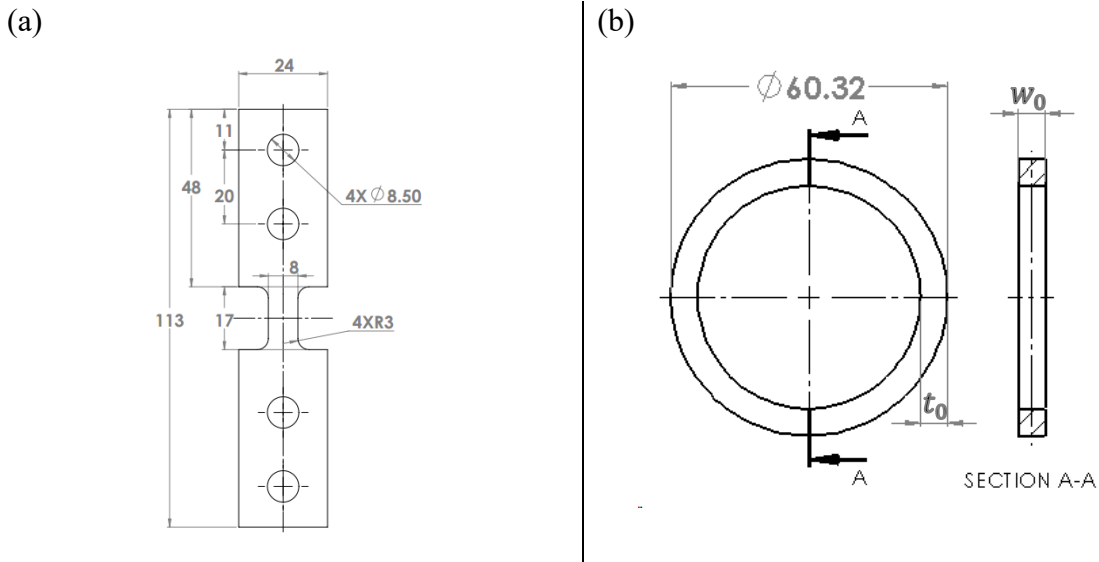
Figure 3-5 Schematic description of (a) dog-bone specimen, and (b) ring specimen.

There are three types of tensile test conducted in this work, 'wet' and 'dry' tensile tests on CPVC dog-bone specimen, and 'dry' D-split tests on CPVC ring specimen.

Treatment of specimens for 'dry' tests was conducted by immersing the specimens in liquid in the way shown in Figure 3-6 (a), illustrated using a ring specimen. Note that CPVC sheet specimens were immersed in acetone for 40 minutes and in primer for 10 minutes, while CPVC ring specimens were immersed in acetone or primer for 30 minutes [29]. As mentioned earlier, the container was shaken every 2 minutes to avoid the specimens stuck to the bottom of the container. Drying time for dog-bone specimens in acetone ranged from 2.5 hours to 984 hours (41 days). In order to maintain flatness, specimens with drying time longer than 23 hours were sandwiched using PE blocks for the first 23 hours, and then uncovered to dry in the fume hood. Those acetone-affected specimens designed to dry less than 23 hours would only be exposed in the fume hood, i.e., specimens drying for 2.5 hours and 6 hours were not compressed by PE panel. Specimens with the drying time of 23 hours would be under compression till the end of drying. Drying time for dog-bone specimens immersed in primer is ranging from 96 hours to 2230 hours, with the first 23 hours being sandwiched, then uncovered to dry in

the fume hood. The length of drying time for acetone-immersed ring specimens was 10.5 days.

In addition to immersion, 'dry' D-split test is also conducted to ring specimen contact with the chemical liquid in a local region on the inner surface, as described schematically in Figure 3-6(b). Chemical liquid (acetone or primer) was reapplied to the local region for every 90 seconds for a period over 2 hours. The inner part of the ring specimen was selected as it is subjected to tensile force during the D-split test, and more likely to fracture for investigation. Other attempts were also made to realize the local exposure of CPVC ring specimen to chemical liquid, as listed in the Appendix. However, these methods had unwanted parts of the specimen being exposed to the chemical liquid. The weight gain was calculated in the same way as specimens after the immersion treatment, i.e.

$$Weight\ gain\ (\%) = \frac{Weight\ of\ specimen\ after\ treatment\ -\ weight\ of\ virgin\ specimen}{Weight\ of\ virgin\ specimen} \times 100.$$

For specimens subjected to the local treatment, D-split tests were conducted on the specimens after drying for at least ten days. Virgin CPVC ring specimen and dog-bone specimen were also tested for reference. All tests were conducted at room temperature.

(a)   (b)
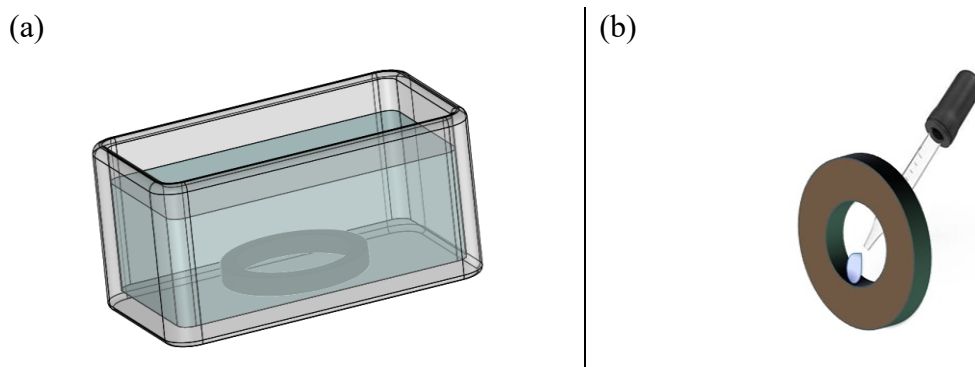
Figure 3-6 Schematic description of (a) whole-body immersion and (b) local contact treatment.

Since CPVC ring specimens were treated either by immersion or local exposure to chemical liquid, as shown in Figure 3-6, the affected region after the treatments should be different in dimensional change by the treatments.

Ideally, in the immersion process, the chemical liquid is diffused into the entire cross-section of the ring specimens through four directions, as depicted in Figure 3-7(a), while

only one direction of diffusion for specimens subjected to local exposure, as depicted in Figure 3-7(b).
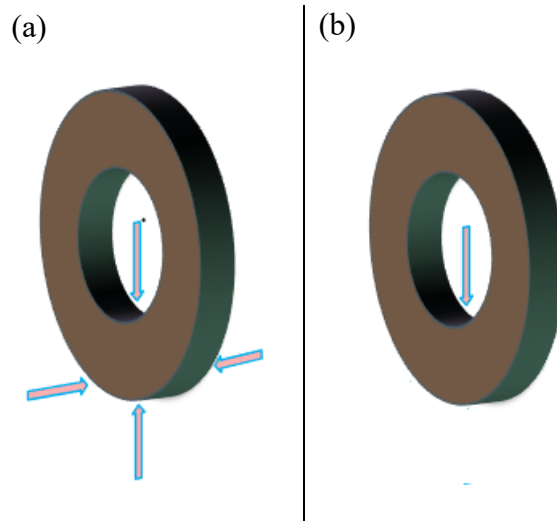
Figure 3-7 Schematic description of diffusion direction for (a) immersion and (b) local treatment.

Based on the previous scanning electron microscopy (SEM) of primer-immersed CPVC ring specimen [29], the extent of diffusion on the cross-section was expected to have a clear boundary to divide the affected and undiffused region, such as the 'core-shell' structure. For the immersed specimens, the ideal division between diffused and undiffused region is depicted in Figure 3-8(a), with the thickness of the shell region increasing with the increase of the immersion time. The ideal diffused region on the cross-section of ring specimen subjected to local treatment is depicted in Figure 3-8(b). As reported previously, the area ratio between the diffused and undiffused regions influence the mechanical property of the specimen [54].
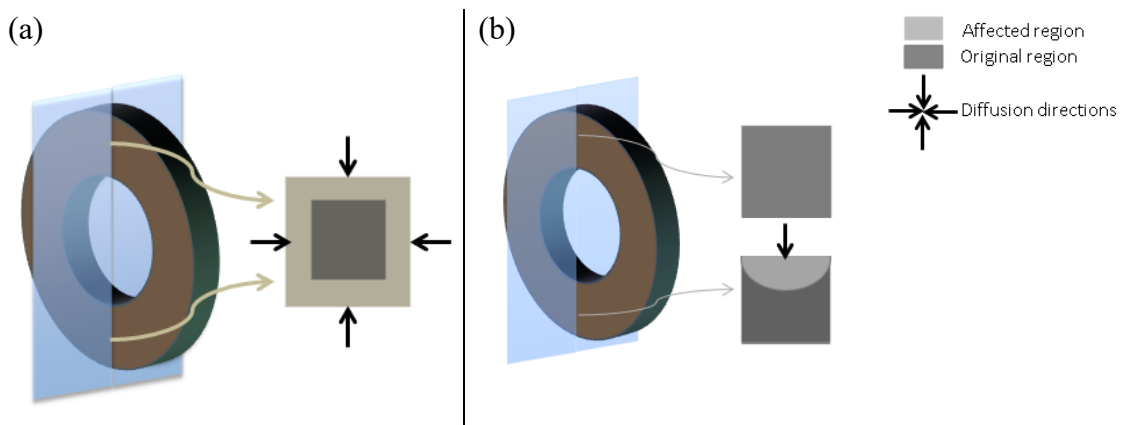
Figure 3-8 Schematic description of the cross-section after different treatment methods.

3.3 Details of mechanical test

Study on the change of mechanical properties for CPVC specimens after exposure to chemical liquids was conducted through the tensile test. This section introduces the tensile tests conducted in the lab. All tests were conducted using Qualitest (Ft. Lauderdale, FL) Quasar 100 universal test machine at the cross-head speed of 1 mm/minute. For each of dog-bone and ring specimens, this section provides a description of test equipment, calculation of engineering stress and tensile test results. Results from tensile tests of dog-bone specimens were further divided into 'wet' test and 'dry' test based on the different test environments.

3.3.1 Equipment and equations of tensile tests

The stroke value of CPVC specimens before the onset of fracture (S_f) in the tensile test are represented as follows, S_{fw} for the 'wet' test, S_{fd1} and S_{fd2} are used for the 'dry' test where the former for acetone-affected dog-bone specimen and the later for the primer-affected dog-bone specimen. In addition, S_{fr} is used for the 'dry' tests to ring specimens. Their value represents ductility of the specimen at the onset of fracture. 'Wet' tests were conducted using the equipment shown in Figure 3-9, and 'dry' test using equipment in Figure 3-10(a).

Engineering stress (σ_{eng}) for dog-bone specimens is calculated based on Eq. *3-2*,

$$\sigma_{eng} = \frac{F}{w_{gauge} \times t_{gauge}} \tag{3-2}$$

where w_{gauge} represents the width of gauge section, t_{gauge} the thickness of gauge section. 'Wet test' uses dimensions of the virgin specimen, and 'dry test' using the dimensions just before the test, i.e., after the drying for the designated periods.
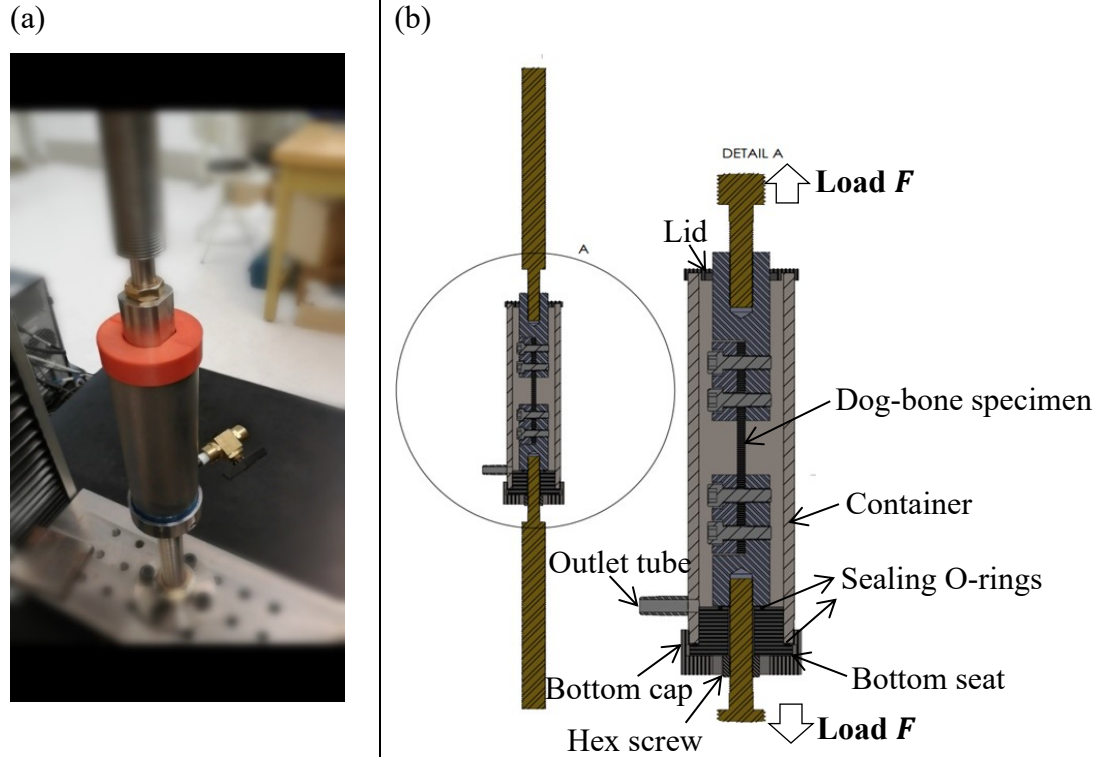
Figure 3-9 (a) Setup of 'wet test' and (b) Schematic description to the inside of the setup (without showing on/off ball valve).

CPVC ring specimens with immersion and local contact treatments, as shown in Figure 3-6 were tested through fixtures schematically shown in Figure 3-10(b). Calculation of the engineering stress for ring specimen is through Eq. *3-3*:

$$\sigma_{eng} = \frac{F}{2 \times w'_0 \times t'_0} \tag{3-3}$$

Where w'_0 and t'_0 represents the dimensions of the immersed ring specimens after drying for the designated length of time. Accordingly, the width(w_0) and wall thickness(t_0) are used for virgin ring specimens, as shown in Figure 3-5(b).
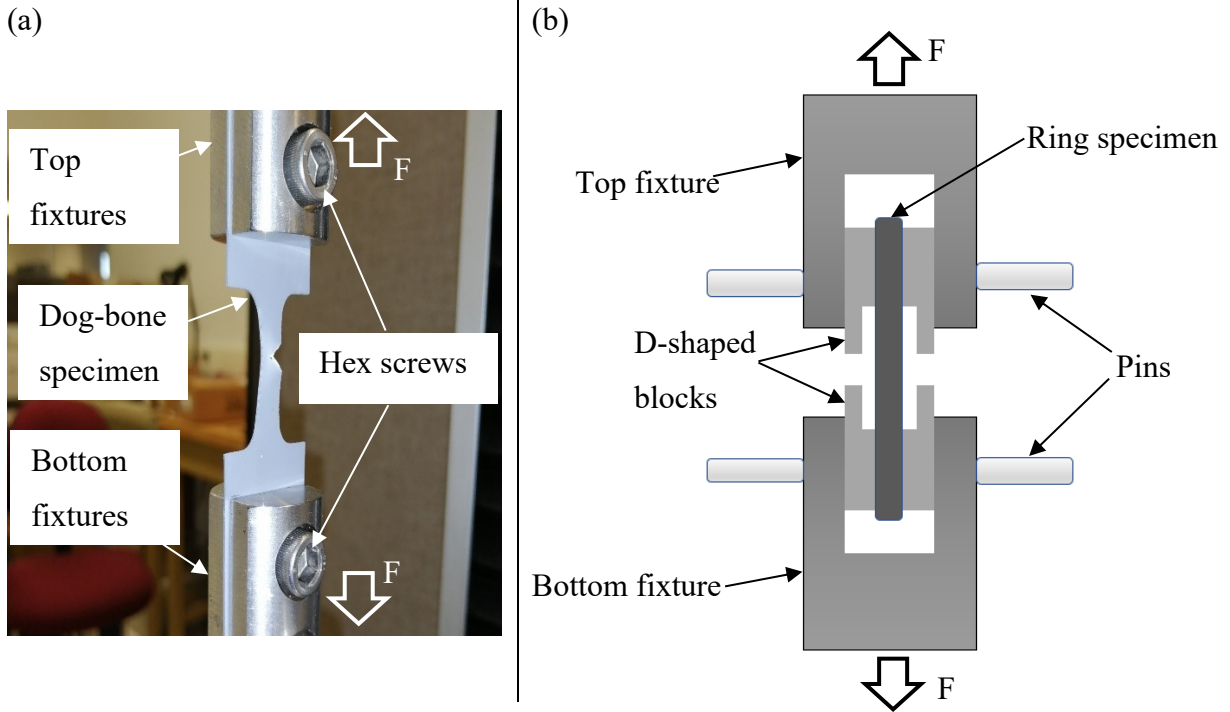
Figure 3-10 Description of (a) 'dry' test for CPVC dog-bone specimen and (b) D-split test for CPVC ring specimen.

3.3.2 Test results of CPVC specimens

Results are presented in groups based on the forms of specimens, i.e., dog-bone specimen and ring specimen. Data for the dog-bone specimen is further separated for the difference in test environments, i.e., 'wet' and 'dry' tests.

3.3.2.1 'Wet' test on CPVC dog-bone specimens

'Wet' test is conducted using the in-house designed fixture shown in Figure 3-9. Immersion time before the commencement of the 'wet' test was 1, 5, 10, 15, 20 or 25 minutes. Acetone was periodically poured into the chamber from the top to ensure that specimens were fully immersed before the start of the test.

Two tests were conducted at each condition. Dimensions in the gauge section of every specimen were measured before the assembly of the fixtures. The cross-sectional area of the gauge section was used to calculate the engineering stress and then plotted as a function of stroke. Yield stress is selected as the peak value on the engineering stress-

stroke curve. For those curves showing no evident peak values, the largest engineering stress during the tensile test was used as the yield stress.

Typical engineering stress-stroke curves are presented in Figure 3-11. It includes the experimental data of virgin CPVC dog-bone specimen and specimens with different length of immersion time in acetone. Only one curve is selected for presentation out of two tests for each condition, and specimens with an immersion time of 25 minutes or longer have a very small peak value to be visible. All of the peak stress and S_{fw} values are summarized in the Appendix. **W0** represents the corresponding values for the virgin specimen.
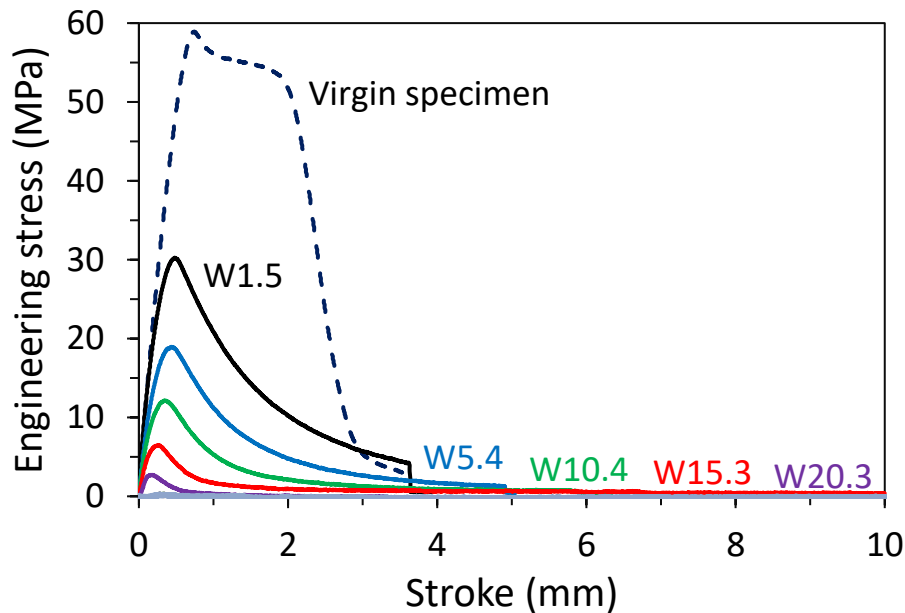
Figure 3-11 Engineering stress-stroke curves of CPVC dog-bone specimens ('Wet test') after different immersion time in acetone, as indicated by the numbers (in minutes). The lowest curve with nearly no peak is the test after the specimen has been immersed for 25 minutes.

Figure 3-11 suggests that with the increase of immersion time, compliance of the specimens increases and the corresponding stroke for the yield point decreases, and the peak stress is reduced to virtually zero after immersion time over 25 minutes. The strokes for the peak stress points is presented in Figure 3-12.
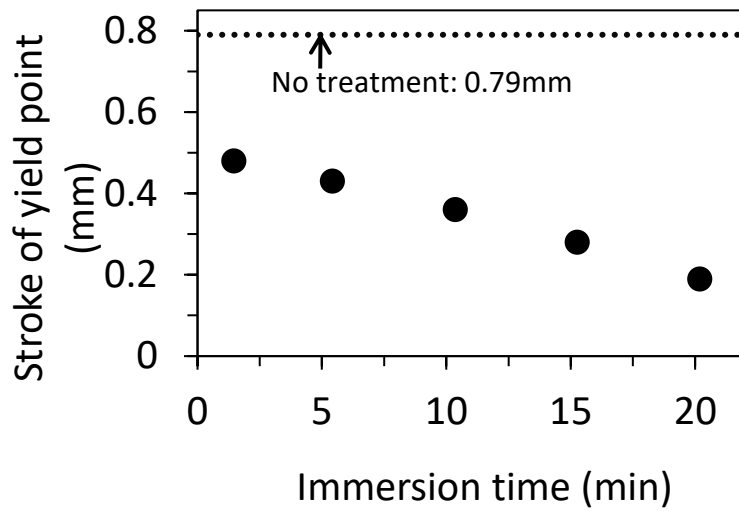
Figure 3-12 Stroke of yield point as a function of immersion time for specimens in 'wet' tests.

Yield stresses for each curve are summarized in Figure 3-13 to represent the change of yield strength as a function of immersion time. It shows that even immersion in acetone for 1.5 minutes could reduce the strength by about 50%, and no strength is detectable for the immersion time longer than 25 minutes.
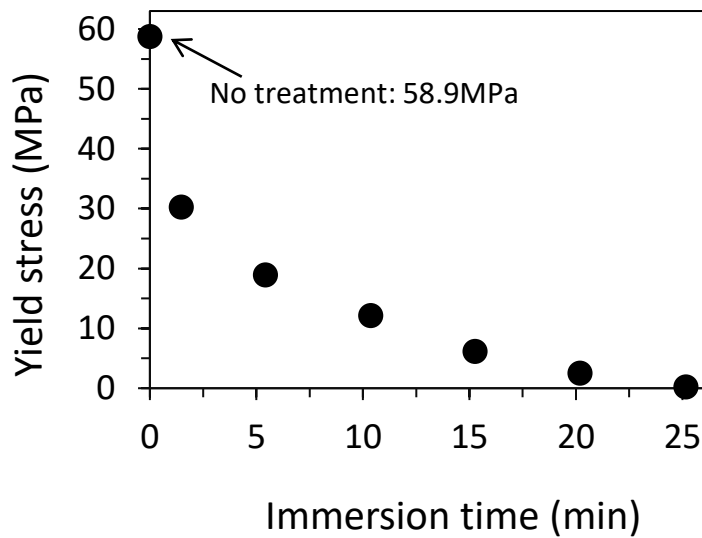
Figure 3-13 Yield stress as a function of immersion time of dog-bone specimens in 'wet test'.

Numbers for S_{fw} represents the stroke values for the onset of fracture in each curve, i.e., the corresponding stroke value where a quick load drop starts. Take the case of the specimen after immersion for 20 minutes as an example, the value of force fluctuated

around zero in the elongation range from about 6 to 8mm. Through zoom-in, it was found that there is a plummet of force from positive to negative in the stroke range from 7.0 to 7.2mm, as shown in Figure 3-14. Then, in the following test, when such a plummet occurred, the specimen was checked immediately and found to be broken. As a result, the corresponding value of elongation at the onset of force drop is denoted as S_{fw}. In the case shown in Figure 3-14, the S_{fw} value is 7.01mm.
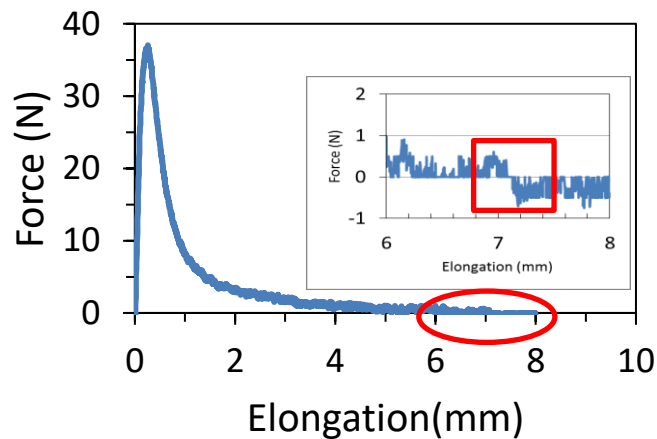
Figure 3-14 'Wet' test result of CPVC dog-bone specimen after immersed into acetone for 20 minutes.

Then, stroke for the onset of fracture for dog-bone specimens from the 'wet' tests is plotted as a function of immersion time, as shown in Figure 3-15. The figure shows that the stroke value increases gradually towards a plateau of about 7.01mm. This suggests that the immersion process could postpone the onset of fracture, and longer the immersion time, bigger the stroke for fracture of the specimen. The delayed fracture suggests that the ductility increases, which is consistent with the ductile rupture of CPVC material reported by Knight [39]. Based on the observations in the preliminary tests, swelling is not visible for the dog-bone specimens in the 'wet' tests with the length of immersion time up to 25 minutes, but longer the immersion time, bigger a curved region appeared around the fracture location in the gauge section, and it is still visible after the drying, which will be discussed later in Figure 3-27.
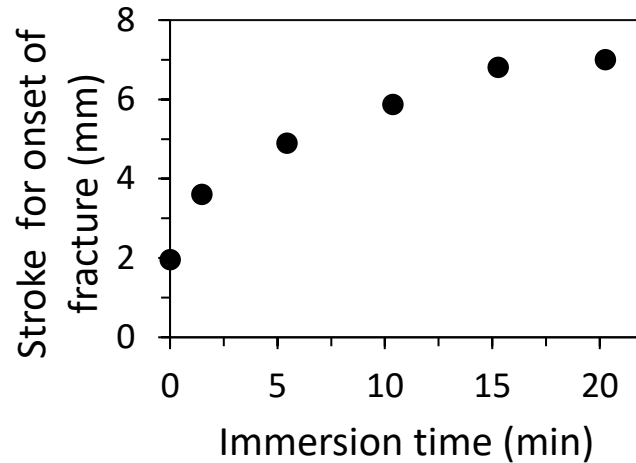
Figure 3-15 Stroke for the onset of fracture as a function of immersion time from the 'wet' test.

3.3.2.2 'Dry' tests on CPVC dog-bone specimens

1) 'Dry' test after immersion in acetone

First, the weight increase change of dog-bone specimens as a function of drying time is plotted in Figure 3-16, where the time is on a logarithmic scale. It can be seen that value for weight increase drops down dramatically at the beginning of the drying process and then decreases gradually later. The last four data points in Figure 3-16 were used to predict the value of weight gain, which should be around 1.04% when the drying time is beyond 1000 hours.

Figure 3-16 Weight increase as a function of drying time for CPVC dog-bone specimens after immersion in acetone for 40 minutes.

The dimensional increase in the gauge section from the immersion is also plotted as a function of drying time, as shown in Figure 3-17 for width and Figure 3-18 for thickness, to be about 1.26% and 0.3% for width and thickness, respectively, at the drying time of 1000 hours.
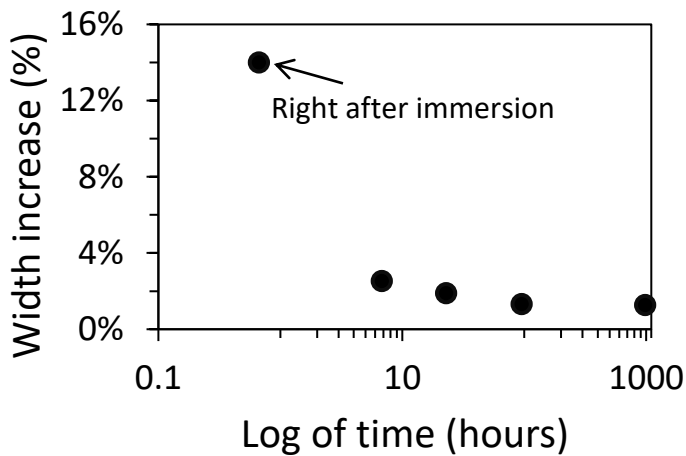
Figure 3-17 Width increase as a function of drying time for CPVC dog-bone specimens after immersion in acetone for 40 minutes.

Figure 3-18 Thickness increase as a function of drying time for CPVC dog-bone specimens after immersion in acetone for 40 minutes.

Typical engineering stress-stroke curves from dry tests on dog-bone specimens immersed in acetone for 40 minutes are presented in Figure 3-19, including results from a virgin specimen as the reference. Only one curve is selected for the presentation out of two tests for shorter drying time, and three tests for longer drying time such as Da984. Values for peak stress and the initial slope of each curve are summarized in the Appendix, as well as the stroke value for the onset of fracture (S_{fd1}), where **D0** represents the value for the virgin specimen. Both yield strength and initial slope show recovery with the increase of drying time.

$$Property\ recovery\ (\%) = \frac{The\ corresponding\ value\ for\ treated\ specimen}{Mechanical\ property\ of\ the\ virgin\ specimen} \times 100$$

Figure 3-19 Engineering stress-stroke curves of CPVC dog-bone specimens ('Dry test') after immersion in acetone for 40 minutes and with different drying time (in hours) as indicated by the number.

As mentioned earlier, the engineering stress in 'dry' tests was determined by dividing the load by the cross-sectional area of the gauge section just before the test. Due to the immersion in acetone, dimensions for the gauge length and thickness increase, but as shown in Figure 3-20, the dimensional increase become negligible after a drying period of 6 hours, with an overall increase of the cross-sectional area is merely 0.18%.
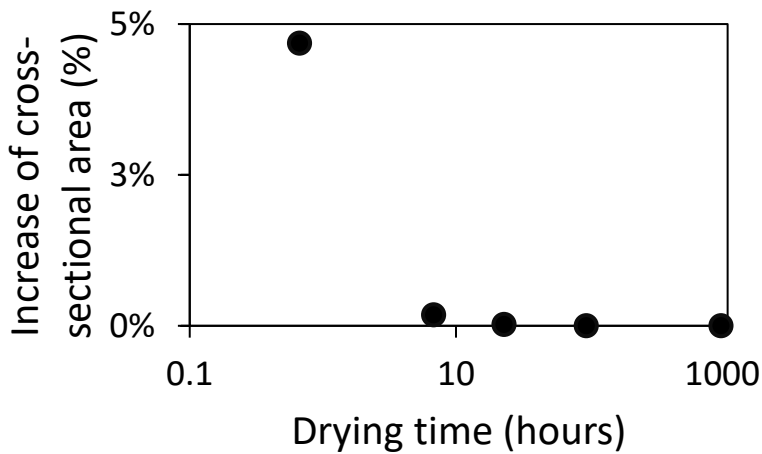
Figure 3-20 The change of cross-sectional area of CPVC dog-bone specimens as a function of drying time.

Yield stress of every curve is plotted as a function of drying time on the logarithmic scale, as shown in Figure 3-21. The figure shows that with the increase of drying time, yield stress of the acetone-treated dog-bone specimen increases towards the value for the virgin specimen. Note that after the drying time of 984 hours, i.e., the very right data point in Figure 3-21, the yield strength reaches about 44.3MPa (around 75.2% of the yield strength for the virgin specimen). However, stroke for the yield point of these specimens does not show a trend of change as a function of the drying time.

The plot shows the fitting equation:

$$Y= 90+22.22 \times \tan^{-1}[\frac{X-1.59}{0.79}]$$

with "No Treatment: 58.9MPa; 0.79mm" indicated. Left axis: Yield stress (MPa), right axis: Stroke of yield point (mm), x-axis: Log (Drying time, Hours). Legend: ○ Yield stress, — Fitting curve, ■ Stroke of yield point.
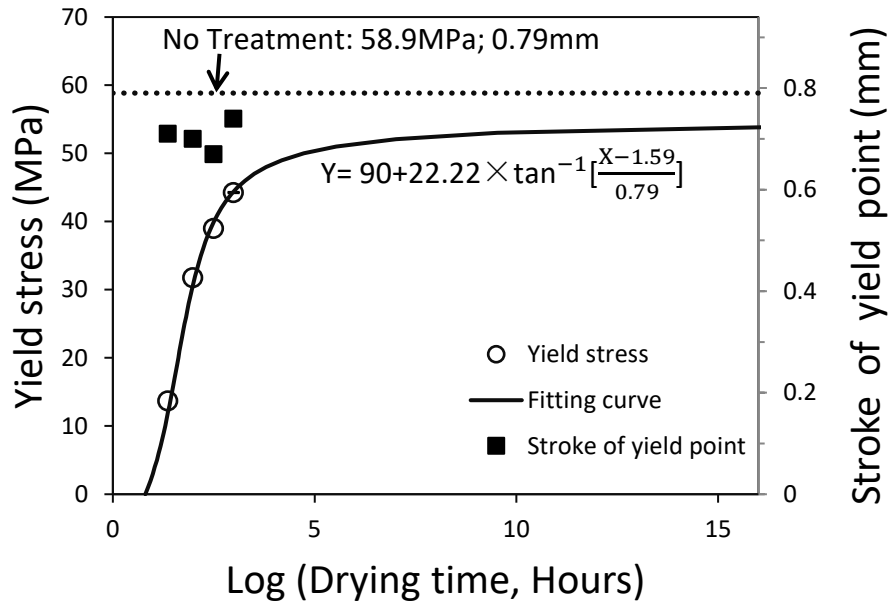
Figure 3-21 Yield stress versus logarithmic of drying time for dog-bone specimens immersed in acetone for 40 minutes.

The initial slope of every curve is also plotted as a function of drying time on the logarithmic scale, as shown in Figure 3-22. It shows that the initial slope has recovered quickly during the drying process, to reach about 83.5MPa after drying for 41 days, with the cross-sectional area also reducing to the original value. This suggests that the elastic modulus can recover to about 68.2% of the value for the virgin specimen.

$$Y= 32+38.46\times\tan^{-1}[\frac{X-1.47}{0.36}]$$
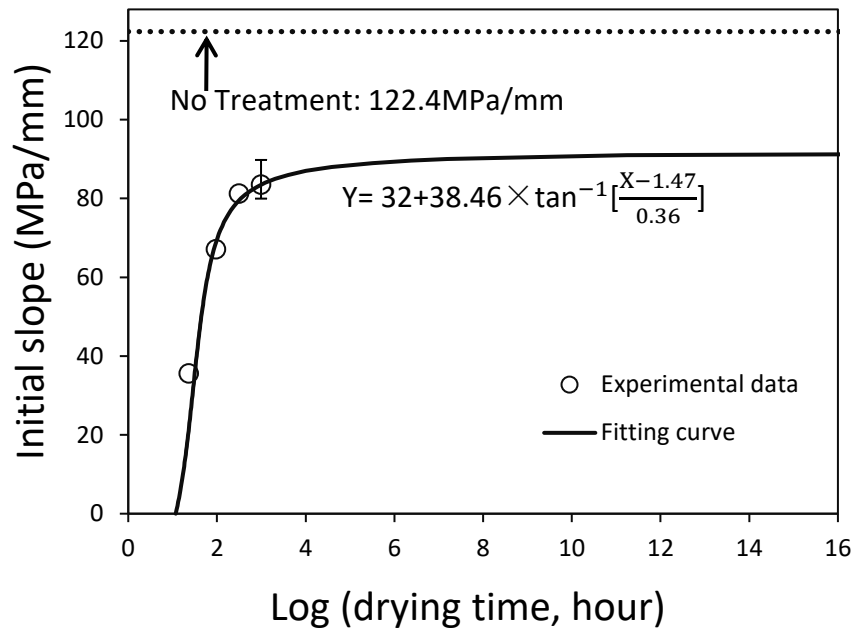
Figure 3-22 Initial slope versus logarithmic of drying time for dog-bone specimens immersed in acetone for 40 minutes.

Yield strength and the initial slope of the dog-bone specimens from the 'dry' test were also fitted using the tangent function, as shown in Figure 3-21 and Figure 3-22. Matlab codes for these curve fitting processes are given in the Appendix. The curve fitting focuses on the prediction of the treated specimen in the long-term drying process. As a result, the experimental results with a very short drying time of 2.5 and 6 hours, which do not fit into the tangent function, are excluded here. These curves suggest that based on the predicted values for the yield strength and initial slope for the CPVC dog-bone specimens after a long drying time, an irreversible damage is introduced by the acetone-immersion treatment. As the fitting curves suggest, the yield strength for CPVC dog-bone specimen can recover only up to about 91% for the virgin specimen, and the initial slope up to 75%.

On the other hand, the phenomenon of ductility increase before the fracture, observed from the dog-bone specimens in 'wet' tests, was also observed from 'dry' test on specimens with drying time up to 41 days. However, the additional stroke from that required for fracture of the virgin specimen, decreases with the increase of drying time, as shown in Figure 3-23.

It is believed that due to the drying process, the stroke for fracture is reduced to be close to the value for the virgin specimen. Nevertheless, as suggested by results from the dog-bone specimens after immersion in acetone for 40 minutes and dried for 984 hours, the stroke for fracture is still much bigger than that for the virgin specimen.
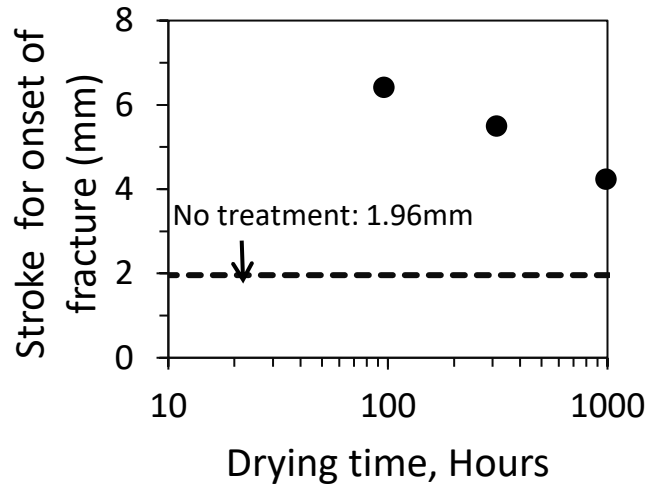
Figure 3-23 Semi-logarithmic plot of stroke for the onset of fracture versus drying time for dong-bone specimens immersed in acetone for 40 minutes.

It noted that for the dog-bone specimens immersed in acetone for 40 minutes and dried for a period shorter than 96 hours did not show any sign of fracture at the end of the test, i.e., with the elongation of 10mm. The specimens showed significant transverse contraction in the gauge section. Therefore, data for drying time less than 100 hours do not provide stroke values at the onset of fracture.

2) 'Dry' test after immersion in primer

The weight increase change of dog-bone specimens immersed in primer for 10 minutes, is plotted in Figure 3-24 as a function of drying time. The figure shows a trend that the weight increase reduces significantly at the beginning of the drying process but is gradually stabilized to be around 9% after drying for over 2000 hours.
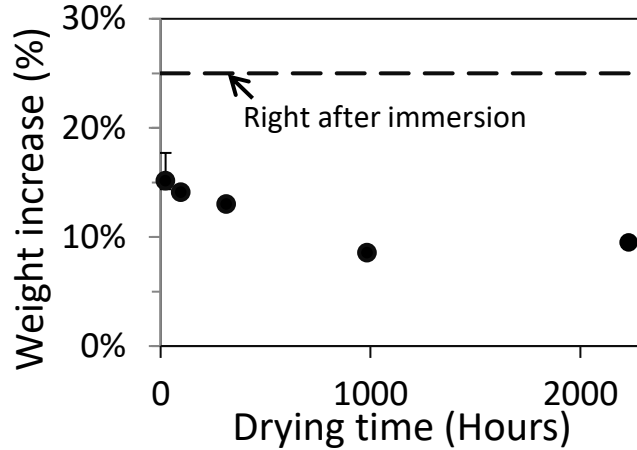
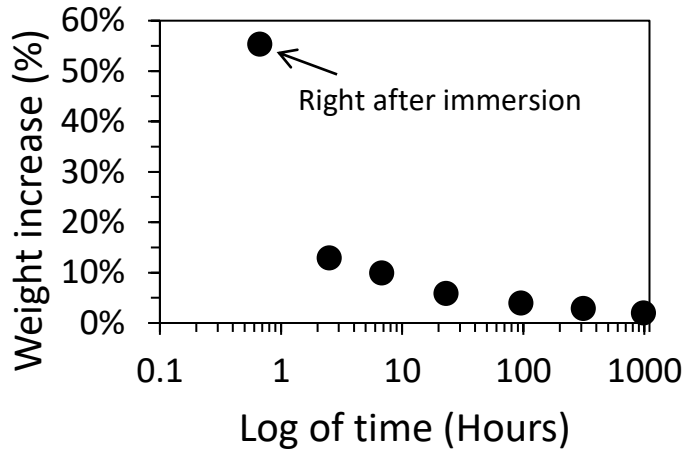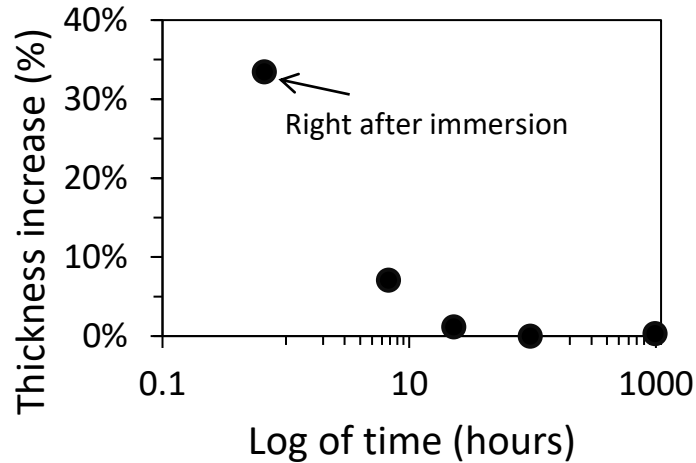*Figure 3-24 Weight increase as a function of drying time for CPVC dog-bone specimens after immersion in primer for 10 minutes.*

Typical engineering stress-stroke curves of CPVC dog-bone specimens immersed in primer for 10 minutes, and dried for various periods are presented in Figure 3-25, along with the result from a virgin specimen as a reference. Only one curve is selected for presentation out of at least two tests for each condition. The peak stress and the initial slope values for all curves in Figure 3-25 have been collected in the Appendix, also the stroke value for the onset of fracture, S_{fd2}.
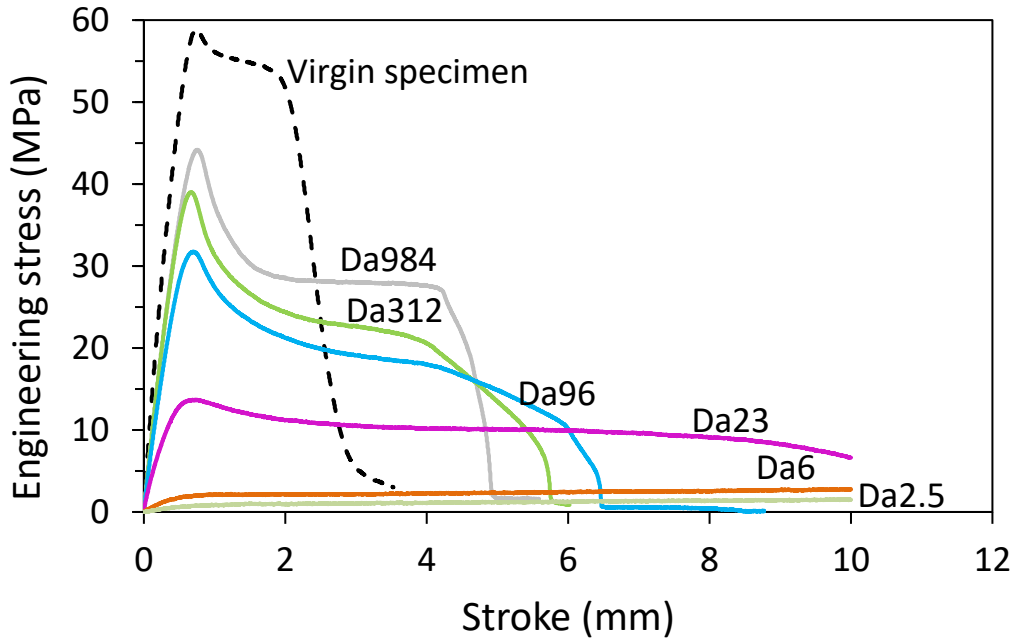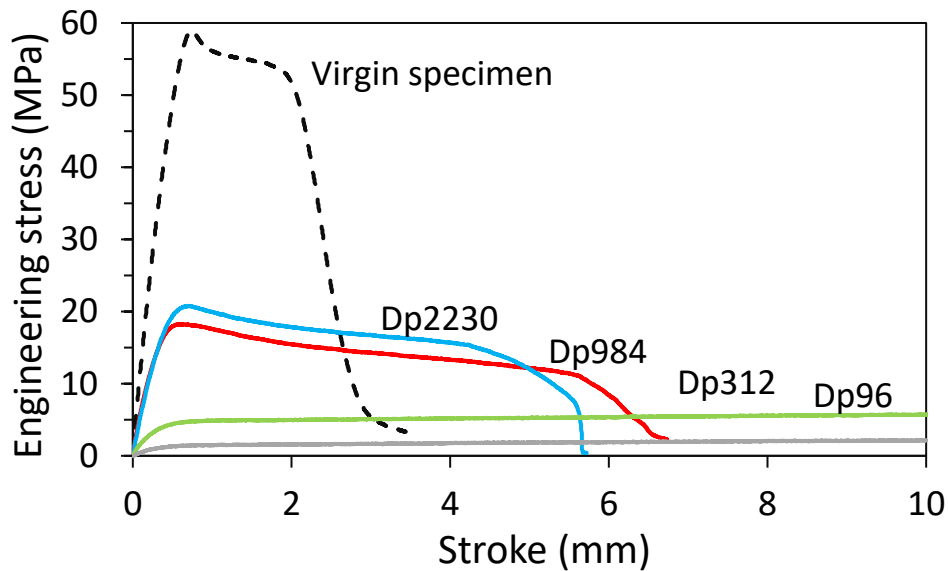

Figure 3-25 Engineering stress-stroke curves of CPVC dog-bone specimens ('Dry test') after immersion in primer for 10 minutes and with different drying time (in hours) as indicated by the number.

35

3.3.2.3 D-split test on CPVC ring specimens

Typical engineering stress-stroke curves from D-split tests on CPVC ring specimens are presented in Figure 3-26, where Figure 3-26(a) represents results from ring specimens treated by whole-body immersion as shown in Figure 3-6(a), and Figure 3-26(b) corresponds to the treatment of local contact to chemical liquid as shown in Figure 3-6(b), where 'IMA' stands for specimens after immersion in acetone, 'IMP' immersion in primer and 'LCP' local contact with primer and 'LCA' local contact with acetone. Numbers after these abbreviations are the number of hours for the treatment. Values for peak stress and initial slope of each curve are summarized in the Appendix, as well as the stroke value for the onset of fracture (S_{fr}), where **V-R** represents the value for the virgin ring specimen.

Specimens used for Figure 3-26(a), were dried for 10.5 days before the D-split test, to be consistent with the drying time used in the previous study after which recovery of the ductility reached the maximum value, and the result for IMP0.5 is taken from the previous work [29], while the rest conducted in the current study. Two duplicated tests were conducted for each condition, and only one curve is selected for the presentation here. Figure 3-26(a) indicates that acetone-immersed and primer-immersed ring specimens after a drying period of 10.5 days could fracture at a stroke smaller than that for the virgin specimen, while acetone-treated specimens show a better strength recovery than the primer-treated specimens. In addition, the former shows that the initial slope of the curve can be almost fully recovered after drying for 10.5 days, but the latter, as reported [29] needs a drying period of 113 days.

The drying period for ring specimens with local contact with acetone and primer, as shown in Figure 3-26(b), is at least 10 days. Three duplicated tests were conducted for each condition, and only one curve is selected for the presentation here. They fractured at a stroke smaller than that for the virgin specimen, but specimen contact with acetone has the strength fully recovered. The specimens contacting with primer, on the other hand, shows a brittle fracture.
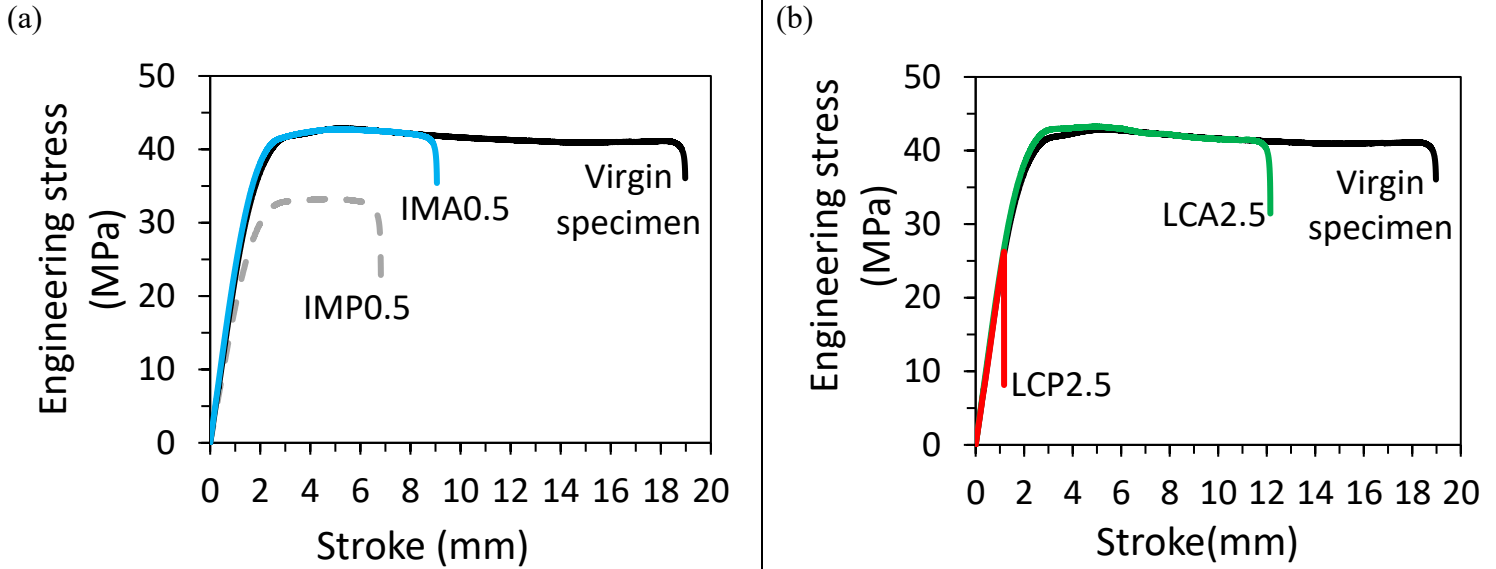
Figure 3-26 Engineering stress versus stroke of CPVC ring specimens after immersion in acetone (IMA), immersion in primer (IMP) [29]*, local contact to acetone (LCA) or local contact to primer (LCP) for different periods in hour, as shown by the number after IMA, IMP, LCA and LCP.*

3.3.3 Description of fractured specimens

CPVC dog-bone specimens after the 'wet' tests in acetone are shown in Figure 3-27. All specimens were fractured within the 10mm elongation, and no apparent dimensional change was found on the specimens. This is consistent with the observation in the preliminary study using CPVC strips, as discussed in section 3.1.

The broken section of specimens with 1- and 5-minute immersions are relatively flat compared to other specimens with a longer immersion time, possibly because of the less dimensional change in the length direction for immersion in acetone for 1 up to 5 minutes.

Figure 3-27 Presentation of acetone immersed CPVC dog-bone specimens in 'wet' tests. From left to right, the immersion time of specimen is 1, 5, 10, 15, 20 and 25 minute(s).

Acetone-immersed dog-bone specimens after 'dry' tests are shown in Figure 3-28, for the length of drying time of 6, 23, 96, 312 and 984 hours for specimens from left to right. Specimen with the drying time of 23 hours is not completely fractured within the 10mm elongation in the 'dry' tests, and specimens with drying time of 6 hours did not break.
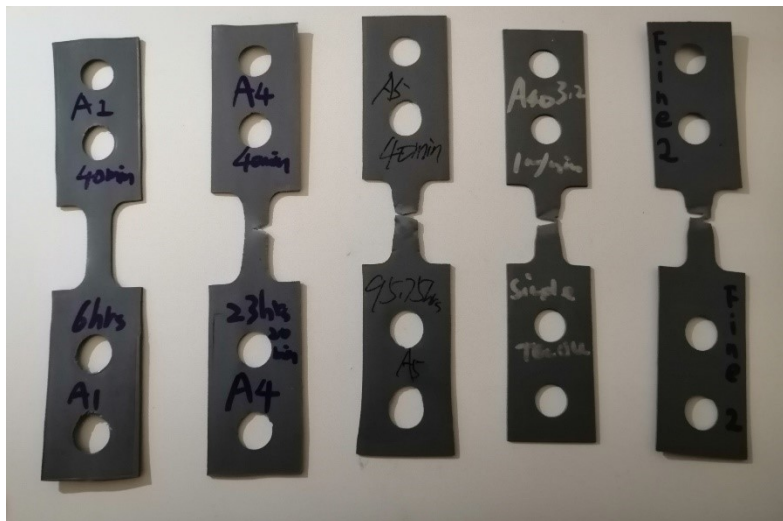
Figure 3-28 Presentation of acetone-immersed CPVC dog-bone specimens in 'dry' test. The length of drying time is 6, 23, 96, 312 and 984 hours from left to right.

'Dry' test of primer-immersed dog-bone specimens are shown in Figure 3-29, the length of drying time was 96, 312, 984 and 2230 hours from left to right. Specimens with drying time less than or equal to 312 hours did not fracture within the 10mm elongation.

38

Comparing to the acetone-treated specimens in Figure 3-28, surfaces of these specimens are relatively rough with loss in light reflection.

Figure 3-29 Presentation of primer-immersed CPVC dog-bone specimens in 'dry' test. The length of drying time is 96 hours, 312 hours, 984 hours and 2230 hours from left to right.

CPVC ring specimens after the D-split tests are shown in Figure 3-30. Specimen after the full immersion for 30 minutes or with a local contact for 2.5 hours, in acetone show, crack initiation within the wrinkled region, while the specimen after local exposure to primer for 30 minutes shows a regular and flat crack.

Immersion in acetone

Local contact acetone the wrinkled region

Local contact, as indicated by circle, to primer

Figure 3-30 Presentation of CPVC ring specimens after D-split tests.

The cross-sections of acetone-treated ring specimens after fracture are shown in Figure 3-31. Difference of the fractured surfaces is the crack initiation and propagation behavior, i.e., crack is from the inner surface of the immersed specimen, while from a corner of the contact region for the local contact specimen as shown in Figure 3-33. Crack propagation of the immersed specimens is along inner surface uniformly, to form nearly horizontal ridges, but the local contact specimens in a radial direction from the corner.
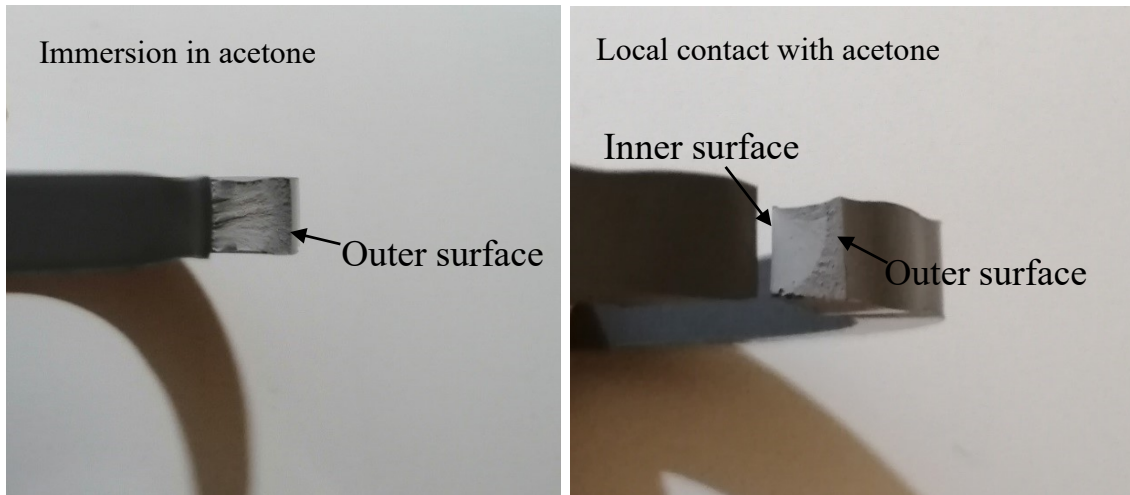
Figure 3-31 Fracture features of CPVC ring specimens after immersion and local contact with acetone.

The cross-sections of ring specimens after the local exposure to acetone and primer are shown in Figure 3-32. The fracture surface of primer treated specimen is relatively smooth and flat and no obvious deformation-introduced roughness was found around the fracture region. Crack for specimens having local contact with primer was also initiated from the contact region, and propagated quickly through the thickness to generate a neat and clean surface, while the specimen contact with acetone has a rough cross-section with a river-flowing pattern and the radial traces for fracture. It is also noted that ring specimens after the local contact to acetone presented a slow crack growth (SCG) behaviour starting from the solvent-affected-zone (SAZ), as illustrated in Figure 3-33.

Local contact with acetone

Inner surface

Outer surface

Local contact with primer

Inner surface

Outer surface
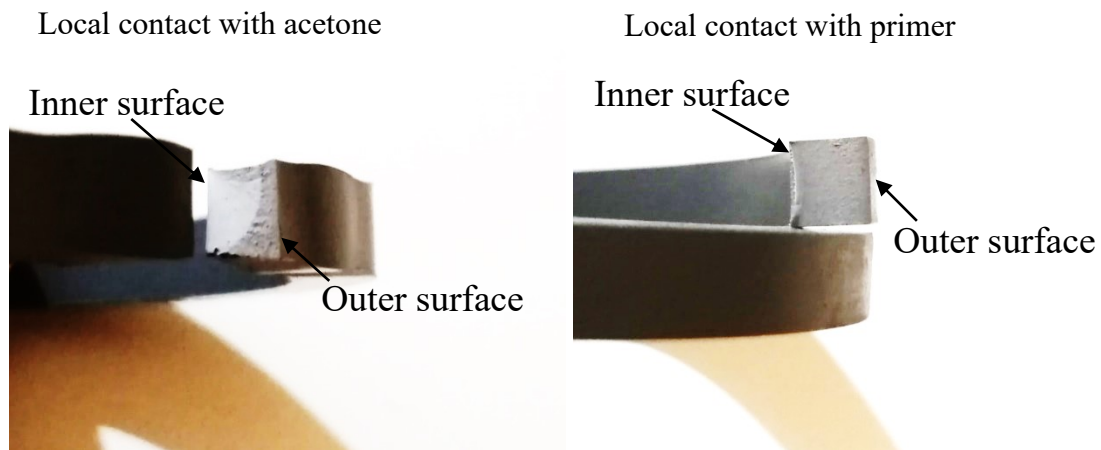
Figure 3-32 Fracture features of CPVC ring specimens after local contact with acetone and primer.

Local contact region

Inner surface

Outer surface

F

F
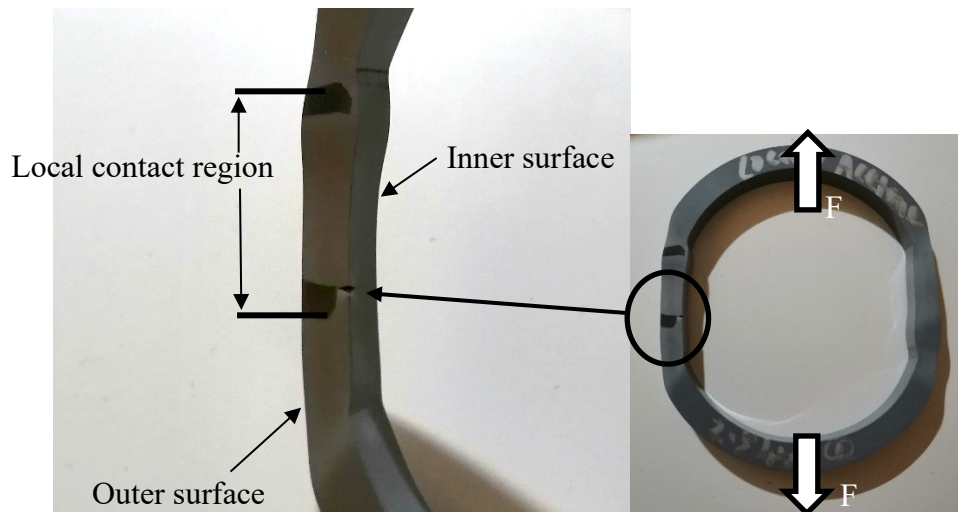
Figure 3-33 Slow crack growth (SCG) of CPVC ring specimen in the tensile test after local contact with acetone.

3.4 Analysis and discussion

This section is first to summarize the 'wet', and 'dry' tests of acetone treated dog-bone specimen to provide a viewpoint about the influence of acetone on mechanical properties of CPVC sheet, and then the results of 'dry' dog-bone specimens are compared to results of 'dry' ring specimens to illustrate the opposite trend of the ductile fracture behavior between CPVC sheet and CPVC pipe specimens.

Most importantly, this section will attempt to provide an explanation for the premature fracture of CPVC ring specimens after the exposure to acetone or primer. This includes the observation of the fracture of ring specimens during tensile test, and a comparison of the test results of CPVC ring specimens with two different treatment methods, i.e., full immersion and local contact.

3.4.1 Influence of acetone on CPVC sheet

Based on the results from 'wet' test, immersion time longer than 25 minutes in acetone would reduce stiffness and yield strength for the dog-bone specimen to nearly a non-detectable level. Although the drying process for 41 days could recover the yield strength and elastic modulus to about 75.2% and 68.2%, respectively, of the virgin specimen according to the 'dry' test results, fracture of the specimens is still in a ductile manner with elongation and transverse contraction in the gauge section more than those for the virgin specimen. Therefore, immersion in acetone increases ductility of CPVC dog-bone specimen, to result in ductile rupture in tensile tests even after majority of the acetone has been removed by the drying process.

3.4.2 Influence of chemical liquids on the ductility change of CPVC sheet and pipe specimens

Trend of ductility change by drying for primer-treated CPVC dog-bone sheet specimens and CPVC pipe-ring specimens were found to decrease with the increase of drying time, but the former is still above the ductility of the virgin specimen and the latter below the ductility of the virgin specimen. This difference is consistent between primer and acetone as the chemical liquid.

In the following discussion, the stroke recovery is defined as the ratio of the stroke value before fracture of the treated specimen to the corresponding stroke for the virgin specimen. A similar definition is given for the yield stress. The yield stress recovery for primer-treated ring specimen is focus on the yield stress for the 'shell' region, while for the acetone-treated ring specimen on the entire cross-sectional region.

Figure 3-34 presents the stroke and yield stress recovery as a function of drying time for primer-treated dog-bone sheet specimens and pipe ring specimens, the latter from a previous study by Chen *et al*. [29]. Comparison between the two trends suggests that the ductility change of CPVC pipe by immersion in primer cannot be predicted using the result of dog-bone specimens from CPVC sheet, as the immersion treatment tends to increase the ductility for the sheet specimens but to decrease the ductility for the pipe specimens, though ductility for both sheet and pipe specimens show a trend of decrease with the increase of drying time. The main difference is that for the sheet specimens, the ductility is decreased towards the value for the virgin specimen, but for the pipe specimens, the ductility decrease to become even less than the ductility of the virgin pipe specimen. Results in Figure 3-34(a) also shows that during the length of drying time between 168 hours and 252 hours, treated ring specimens show a slightly larger value for the stroke recovery than the other drying periods.

(a)

(b)
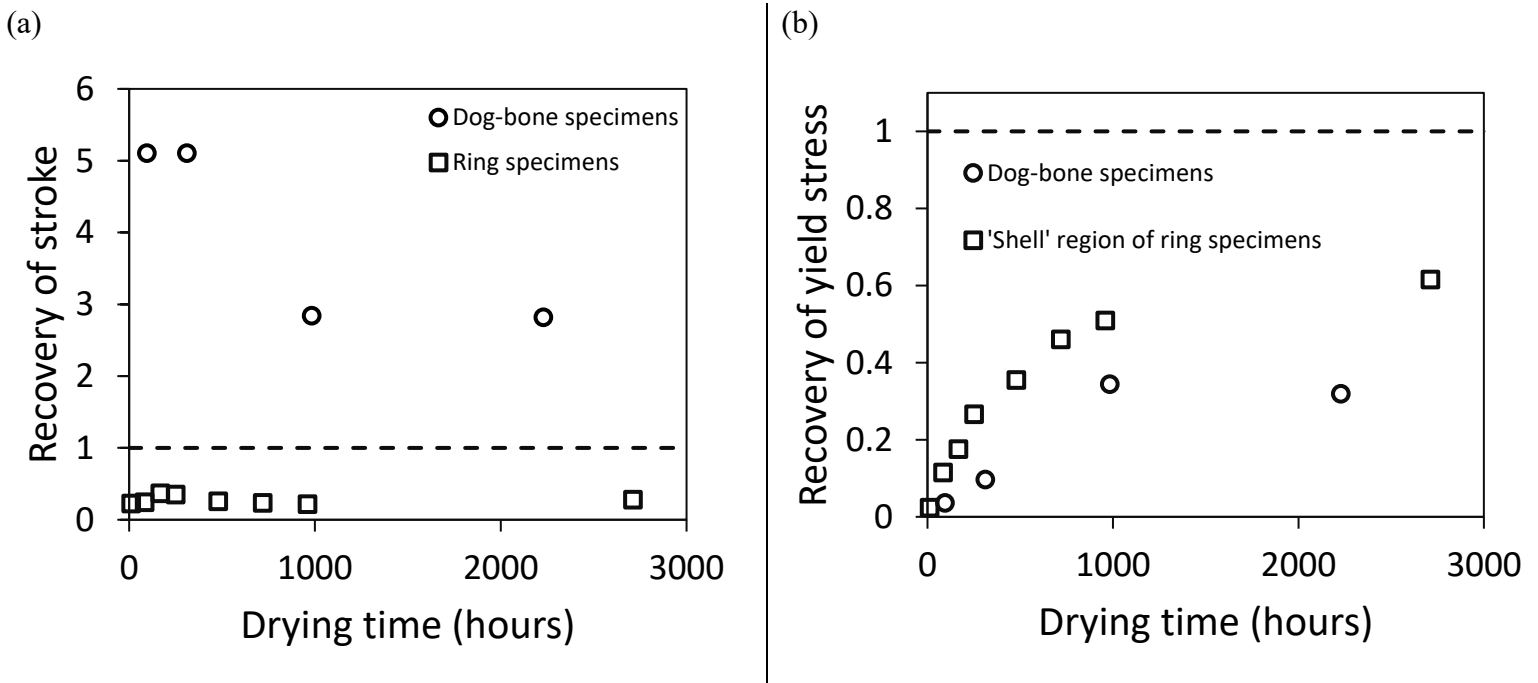
Figure 3-34 Comparison of recovery of stroke and of yield stress for CPVC plate specimens and pipe specimens [29] *after immersed in primer.*

Stroke recovery and yield stress recovery for acetone-treated dog-bone specimens and ring specimens as a function of drying time are also plotted in Figure 3-35. The CPVC sheet specimens show increase of ductility from that of the virgin specimen, even the amount of increase is gradually decreased with increase of drying time, while the ring

specimen shows decrease of the ductility from the virgin specimen, as in Figure 3-35(a). Note that the length of immersion time for CPVC ring specimen in acetone was 30 minutes the same as that used for the primer treatment in the previous study [29].

(a)

(b)
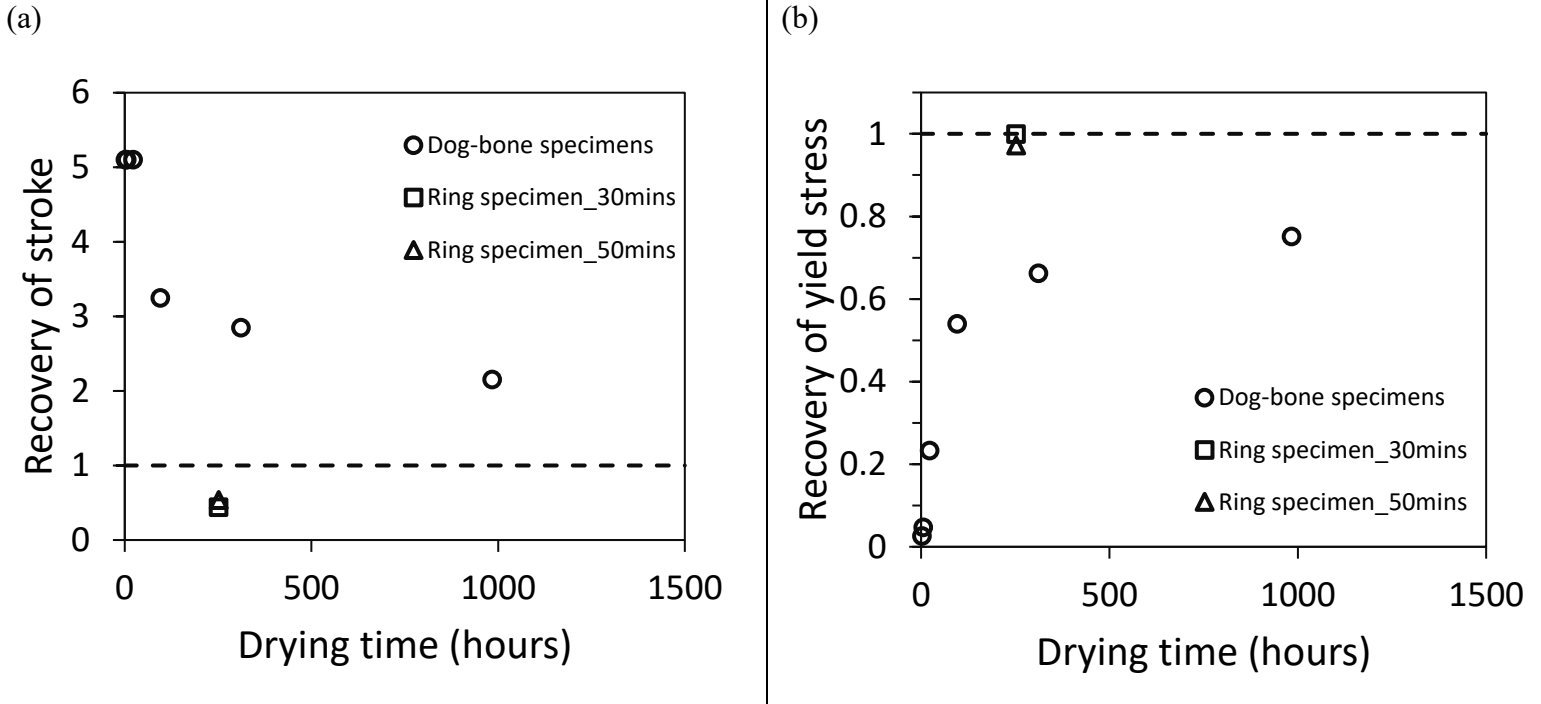
Figure 3-35 Comparison of recovery of stroke and recovery of yield stress for CPVC dog-bone specimens and pipe specimens after immersed in acetone.

Furthermore, based on the results shown in Figure 3-34(a) and Figure 3-35(a), even though ductility of CPVC ring specimens decreases by both the primer and acetone treatments, the degree of ductility decrease depends on the type of chemical liquids that contact the specimens.

The ductility difference of stroke between sheet and ring specimen in Figure 3-34(a) and Figure 3-35(a) does not appear on the yield stress, and overall pipe specimens or regions within pipe specimen after chemical treatment have a better recovery rate than sheet specimens on yield stress, as shown in Figure 3-34(b) and Figure 3-35(b).

Note the acetone-treated CPVC ring specimens with specific drying time have also been used to identify the reason of early fracture in the following section.

3.4.3 Discussion about premature fracture of CPVC ring specimens after the exposure to chemical liquids.

Exploration to the ductility decrease of chemical liquid treated CPVC ring specimens, is through comparison of the fully immersed specimens and specimens with local exposure to the chemical liquid.

The D-split test results of CPVC ring specimens after immersion in chemical liquids, and after local contact as shown in Figure 3-26, is rearranged in Figure 3-36, which could compare the influence of different treatments to ring specimens from the same chemical liquid. For example, in Figure 3-36(a) specimens with either immersion or local contact to acetone have decreased ductility from that for the virgin ring specimen. On the other hand, primer would decrease the ductility and the yield strength of ring specimen, as shown in Figure 3-36(b). Overall, Figure 3-36 suggests that ring specimens after local exposure to chemical liquids also have ductility decreased compared to that for the virgin specimen.
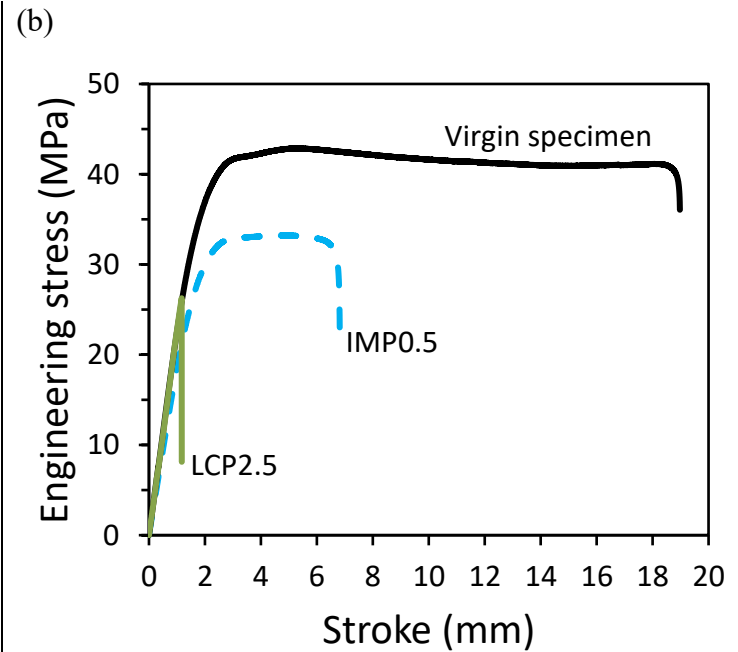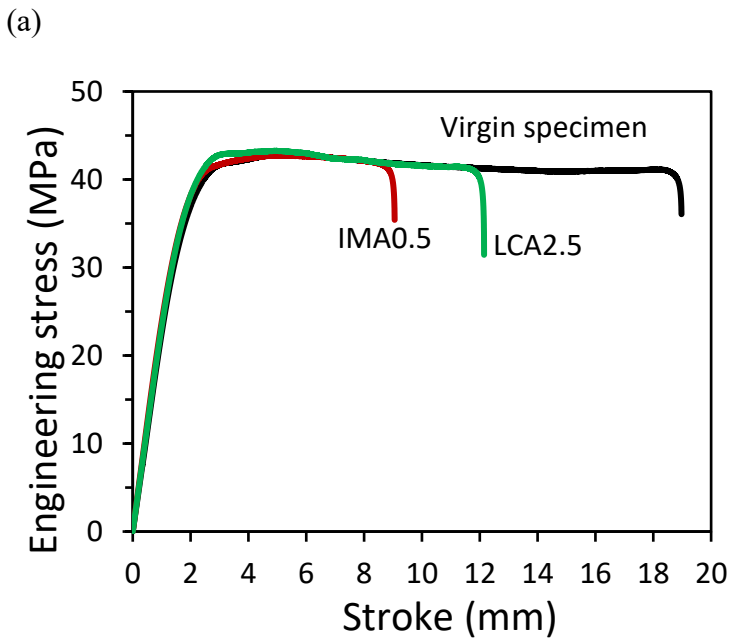
(a)

(b)

Consider the slow crack growth (SCG) behaviour of ring specimens after the local contact to acetone, presented before in Figure 3-33. The crack initiation is schematically illustrated in Figure 3-37, which also illustrates the crack growth to the unaffected region of the ring specimen along the dotted line. Although, the actual route for the crack propagation may be different from specimen to specimen, as mentioned in a previous study for the cause of cracking [29], due to the different coalescence of cracks on a cross-section or the defects on the border between the 'core' and 'shell' region on the cross-section, the generation of a crack due to the presence of the affected region and the associated stress concentration resulted in a premature, brittle fracture of the specimen.

Ring specimens after the local contact to primer, also encountered an early fracture and the fracture appeared in the affected region. But because the fracture is a process of very quick development, it is difficult to capture the different stages for initiation and propagation.
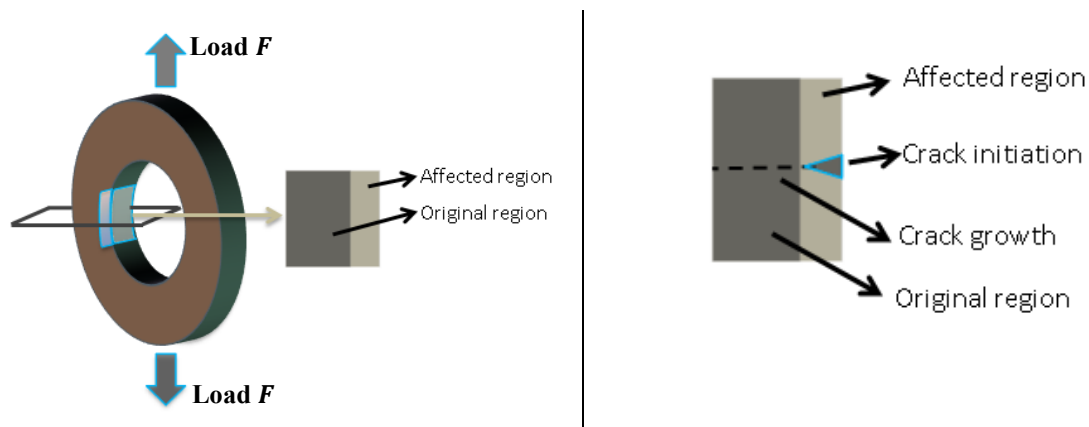
Figure 3-37 Schematic illustration of tensile test for ring specimen after local contact treatment, and the schematic description of fracture mechanism.

The appearance of ductility decrease for CPVC ring specimen with two different treatments, i.e., immersion and the local contact to a chemical liquid, suggests the possibility that the crack was first initiated in the chemical liquid affected region, due to its lower resistance to tensile loading. The presence of the crack reduced the load-carrying ability of the specimen, and an early fracture occurred [55].

Note that the premature crack initiation of ring specimens after local contact with primer may lead to brittle fracture [56], which provides some explanation for the environmental stress cracking (ESC) of CPVC pipelines that are contaminated by chemical liquid [57][58][59]. Except for contact to chemical liquids, presence of premature fracture on CPVC pipeline in industrial service may also be caused by other reasons such as the potential stress concentrations due to pipeline design and installation [60], and the working environments that involve heating and UV light. Therefore, more studies are needed to fully understand the causes for ESC.

Chapter 4 Finite element simulation of the force-elongation relationship of solvent-treated CPVC sheet

Based on the tensile test results of CPVC dog-bone specimens, the analytical modelling using the phenomenological approach was employed to simulate all phases of the force-elongation curve before the onset of fracture. Contents for this chapter include an introduction to the phenomenological approach, some features of the FE model, criteria used for evaluating the stress-strain relationship, and divisions of entire strain range of specimen in tensile testing for the governing laws. Finally, the equivalent stress-strain relations of acetone-affected CPVC dog-bone specimens were compared to those specimens affected by primer.

4.1   Constitutive model based on the phenomenological approach

This approach is one of the three methods that use numerical simulations to investigate the stress-strain relations of polymer deformation. The other two approaches were called (a) slip-link (or tube models) that reckons response from chain entanglements to deformation, and (b) models consider relations between molecular interactions and deformation [61]. Research in this work is based on the phenomenological approach of the FE method.

The phenomenological approach requires developing constitutive models that govern stress response to macroscopic deformation of the specimen. Stress response to deformation in different strain ranges were built up by a set of constitutive equations with various parameters. This approach could mimic the elastic-plastic deformation with necking initiation and propagation in the polymeric materials [62][63][64][65][66], and the rate-dependent or rate-independent deformation at the macro scale [67][68]. This approach has also been used to simulate the viscoelastic deformation [69][70], the time-dependent behavior for rate reversal during creep [71][72], and the response of polymer under high-speed dynamic loading [73].

In this phenomenological approach, inputs of material properties to an FE model are governed by the constitutive equations in which the unknown parameters are determined through iterations. Input of material properties to the FE model is calibrated by the

experimentally determined force-elongation relationship of CPVC virgin specimen and those specimens after treatment with chemical liquids. Considering chemical liquids may soften specimens and introduce the time-dependent deformation behavior [61], creep was also considered as material information for simulations using the FE model.

4.2 FE modelling and illustration of application to simulate the tensile test of CPVC virgin dog bone specimen

Force-elongation relations in this section coms from the tensile tests with loading speed of 1mm/min. The force-elongation relation could be separated into the linear, non-linear, necking, strain hardening and fracture stages with a quick load drop. The simulation work focused on stages from the linear to the strain hardening deformation. Given the thin sheet specimens used in the current work, the simulation would be based on the plane stress in tension, due to little strain generated along the thickness direction.

FE modelling was based on three-dimensional (3-D) dog-bone specimen. The model was developed in ABAQUS Standard (version 6.12). The 3-D dog-bone model consisted of (C3D20R) 20-node quadratic brick with reduced integration in the gauge section and totally over 13,200 nodes, were used to determine the force-elongation relationship under the displacement control.

Due to the geometric symmetry of the dog-bone specimen, the FE model was half of the length and width for the specimen shown in Figure 3-5, i.e., one-quarter of the whole specimen. Necking of FE model was introduced by tapering width in the gauge section so that the gauge width a gradually decrease to arrive at the smallest width located at the middle of the gauge section where the reduction is 0.2%. The FE model has also been partitioned to mesh, as shown in Figure 4-1. The fine-meshed region includes the gauge section whose mechanical performance is of interests, as well as the region that is free of clamping by fixtures, that is, the area up to 8mm above the gauge section. Other areas of the FE model have coarse mesh to save calculation time, as compression by the fixture during tensile tests is not the focus of the study.
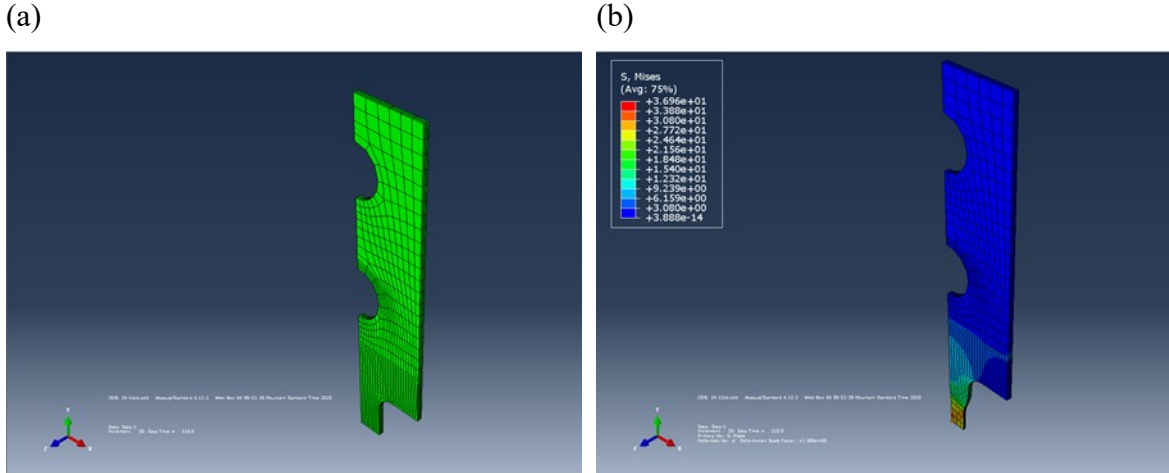
Figure 4-1 Presentation of the meshed quarter FE model for FE simulation (a) and a typical simulation result (b).

Criteria used to evaluate the stress-strain relationship were obtained from the tensile testing: (i) peak force value and the corresponding elongation, (ii) load-displacement curve profile at the initial of necking process, i.e., the load drop phase and (iii) flow force level during the neck propagation. When the FE models could satisfy the above criteria, the stress-strain relationship of specimen was deemed to be successfully established.

The elastic-plastic deformation of the FE simulation was governed by the stress-strain relations in Equation 4-1 to Equation 4-4. These four equations were also employed to simulate those tensile tests results for CPVC dog-bone virgin specimens and specimens with immersion treatment in acetone or primer. In some cases, the FE model of treated specimen needs Equation 4-5 to consider creep deformation in the post-yield stage in the force-stroke relations.

$$\sigma_{(\varepsilon)} = \begin{cases} \dfrac{3}{2(1+v)} E\varepsilon & for\ \varepsilon \leq \varepsilon_y & \text{Equation 4-1} \\[2mm] d\left[\left(a(\varepsilon+b)\right)^{c-1} - \left(a(\varepsilon+b)\right)^{-c}\right] + e & for\ \varepsilon_y < \varepsilon \leq \varepsilon_n & \text{Equation 4-2} \\[2mm] \alpha k\varepsilon^N & for\ \varepsilon_n < \varepsilon \leq \varepsilon_t & \text{Equation 4-3} \\[2mm] k\exp(M\varepsilon^\beta) & for\ \varepsilon > \varepsilon_t & \text{Equation 4-4} \end{cases}$$

$$\dot{\varepsilon}^{cr} = A\sigma^n t^m \qquad\qquad for\ \varepsilon_n < \varepsilon \leq \varepsilon_t \qquad \text{Equation 4-5}$$

The overall stress-strain relations given in Equation 4-1 to Equation 4-5 are for σ as the equivalent stress and ε as the equivalent strain, whereas, the entire stain range is

separated by ε_y as the critical strain for the transition from linear to non-linear deformation, ε_n the strain for the onset of necking, ε_t as the transitional strain for the strain-hardening and $\dot{\varepsilon}^{cr}$ as the equivalent creep strain rate. E is Young's modulus, υ is Poisson's ratio, and t is the time measured from the onset of necking. The rest of the parameters (a, b, c, d, e, α, k, N, M, β, A, n, and m) are user-defined constants. Note that β value in 4-4 is fixed at 1.8, following what has been done previously [74], to provide a fast strain hardening rate. Values of other parameters were determined through iteration.

Material input file to the FE model has more than 1500 discrete points in a table format. With such a high density of discrete points, minor adjustment is allowed by ABAQUS to satisfy continuity in the stress-strain relationship, especially to create a smooth connection in the transitions between the governing equations. The iteration process to determine values for the parameters was operated by considering all equations at the same time [75], that is, output of the FE model could be simultaneously experiencing all deformation stages from linear to strain hardening.

Figure 4-2 compares the curve generated from the FE simulation result to the tensile test result of virgin CPVC dog-bone specimen, including linear and non-linear deformation, necking and strain hardening. Results from the FE model are also verified by comparing Young's modulus (E) of CPVC in the literature and the value obtained from this work, the former in the range from 2.9GPa to 3.4GPa [58], and the latter 3.1GPa.
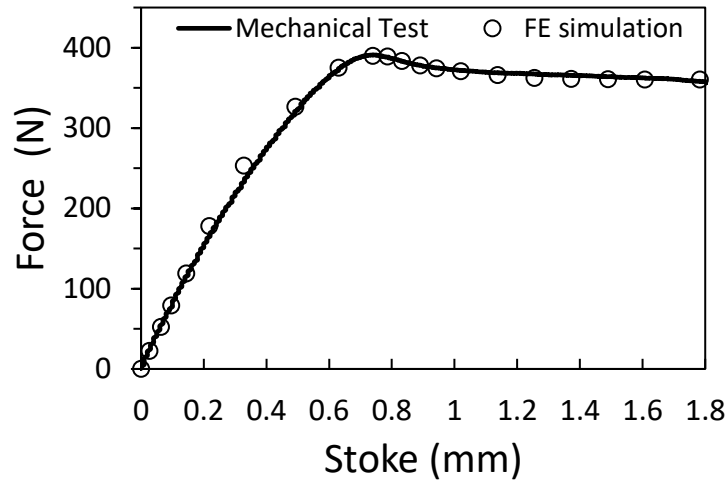
Figure 4-2 Comparison of simulation result with the tensile test result for CPVC virgin dog-bone specimen.

Figure 4-3 presents the equivalent input stress-strain relationship to the FE model in order to match the test results shown in Figure 4-2. Note that the number of data points plotted in Figure 4-3 was dramatically reduced from the numbers used in the simulation model to improve the clarity of the presentation.
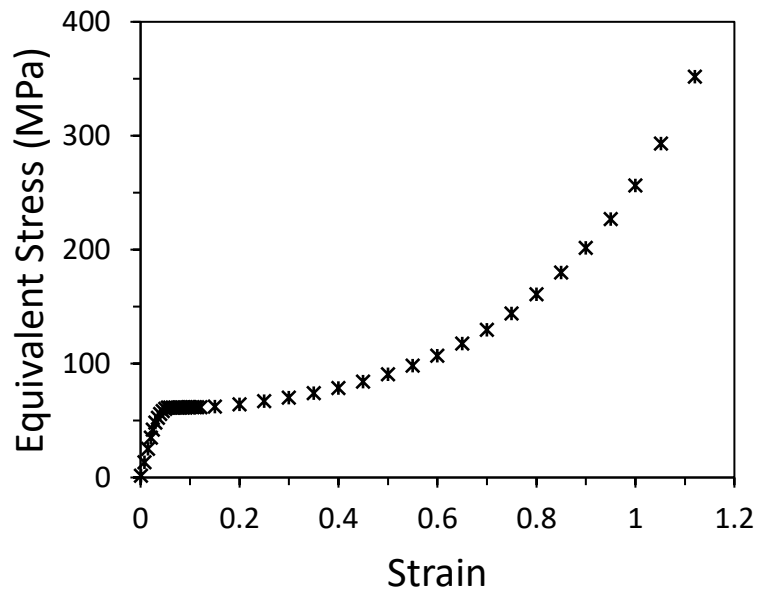
Figure 4-3 The equivalent stress-strain relation input into the FE model.

Table 4-1 listed values for each parameter in Equation 4-1 to Equation 4-4 to determine the equivalent stress and strain relationship plotted in Figure 4-3. It is found that one set of values for parameters of Equation 4-4 is not sufficient to simulate the behavior of strain hardening of CPVC in the tensile tests. This is resolved by subdividing the strain range for Equation 4-4 into several sections, all governed by Equation 4-4 but with different values for the parameters. This subdivision is known to be needed for cases that shows a relatively flat region after the necking in the force-stroke curve before the onset of quick load drop. Creep deformation, Equation 4-5, was found to be unnecessary to simulate the force-stroke curve of virgin CPVC virgin dog-bone specimen.

Table 4-1 Values of parameters in the constitutive equations for FE model of virgin CPVC 3-D dog-bone specimen.

Linear elastic in		E(MPa)	3100
Equation 4-1		ν	0.385
Non-linear deformation in Equation 4-2		a	7
		b	0.02
		c	0.15
		d	-20
		e	146.5
Hollomon's equation for plastic deformation in Equation 4-3		αk	123.7
		N	0.001
Strain hardening deformation in Equation 4-4	Section1	k	119.8
		M	1.6
		β	1.8
	Section2	k	120.3
		M	1.54
		β	1.8
	Section3	k	130.5
		M	1.42
		β	1.8

	k	170.6
Section4	M	1.2
	β	1.8

The iteration process determined the values of each parameter in the constitutive equations and established the specific strain range for each of the stages during the deformation. For instance, the strain range for the strain hardening stage is 0.131~1.48 for virgin dog-bone specimen, which has been further separated into four substages, each with a specific strain range. Note that number of substages does not have to be four, as long as results from the FE simulation agree with the results from the tensile test. As illustrated in the previous work [76][77], this phenomenological FE approach has a reasonable efficiency in establishing the stress-strain relationship for materials that experience inelastic and large deformation, such as polymers.

Table 4-2 The strain range for each of the constitutive equation in simulation of the tensile test of CPVC virgin dog-bone specimen.

Linear elastic in Equation 4-1		0~0.02
Non-linear deformation in Equation 4-2		0.021~0.052
Hollomon's equation for plastic deformation in Equation 4-3		0.053~0.13
Strain hardening deformation in Equation 4-4	Section1	0.131~0.27
	Section2	0.271~0.83
	Section3	0.831~1.14

4.3　Comparison of equivalent stress-strain of acetone and primer treated CPVC sheet specimens

Test results of CPVC dog-bone specimens with treatment in acetone or primer have been simulated using the set of constitutive equations mentioned above. Since the thickness of the sheet specimens used in the study is very small, the immersion process is expected to be able to generate a relatively uniform concentration of the chemical liquids along the thickness direction [78]. An attempt has been made to add Equation 4-5 to the other equations for simulation of the specimens that were treated with acetone with different drying time from 312 or 984 hours. As this phenomenological approach allows separation of constitutive equation for creep deformation from the elastic-plastic counterpart [79][80], the study on the creep behavior during the post-yielding deformation, especially during the neck forming process, is relatively straightforward.

However, it was discovered from the study that the creep equation is not needed to simulate the deformation behavior which could be regenerated with a reasonable accuracy based on Equation 4-1 to Equation 4-4, as shown in Figure 4-4. This may be due to the short time period used for the tensile tests in the present work, often completed in less than 2 minutes [80]. Note that for the elastic deformation, Poisson's ratio (ν) in Equation 4-1 is assumed have a fixed value and is equal to the value for the virgin CPVC.

The simulation results of dog-bone specimens after immersion in acetone for 40 minutes or in primer for 10 minutes, and dried for various periods of time are presented in Figure 4-4, using open circles and comparted with the test results. Reasonably good agreement is obtained between the simulation and the tensile test.

(a)　　　　　　　　　　　　　　　　　　　　　　　　　　(e)

(b)

(f)

(c)

(g)

(d)

(h)

56
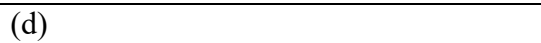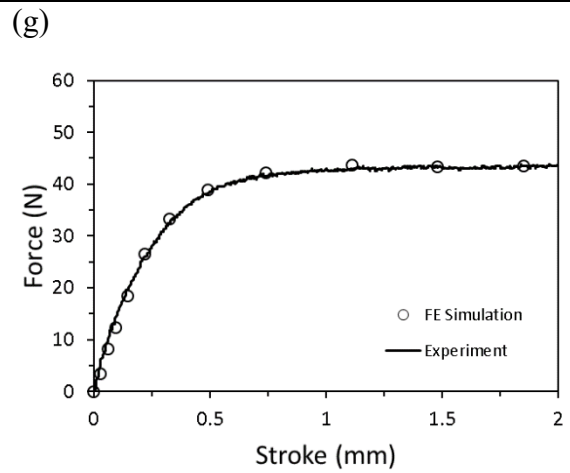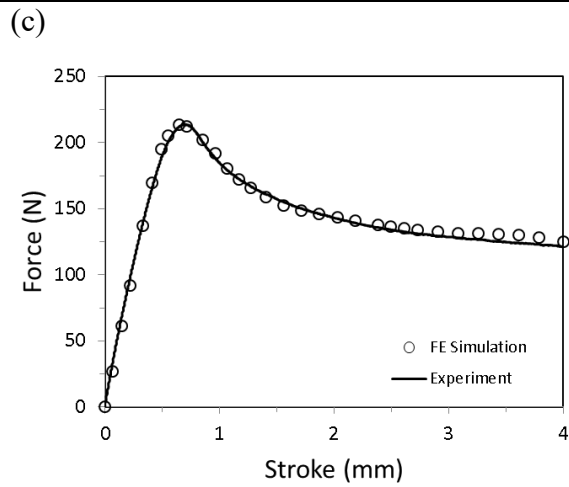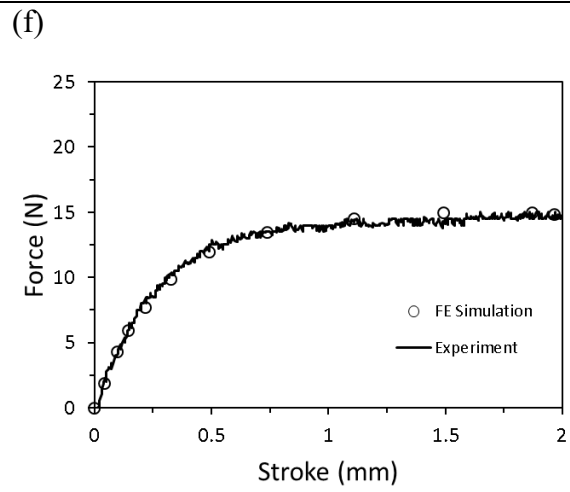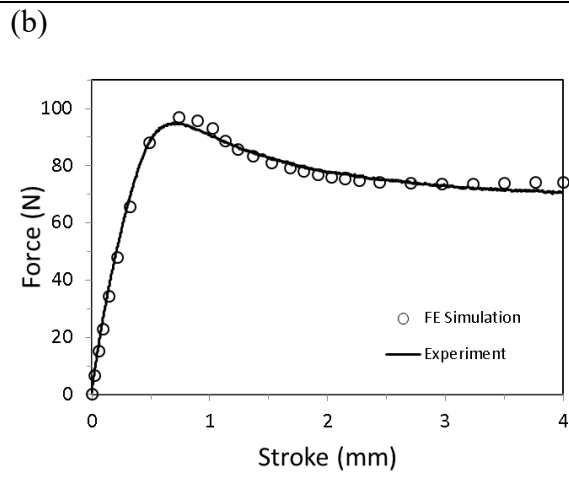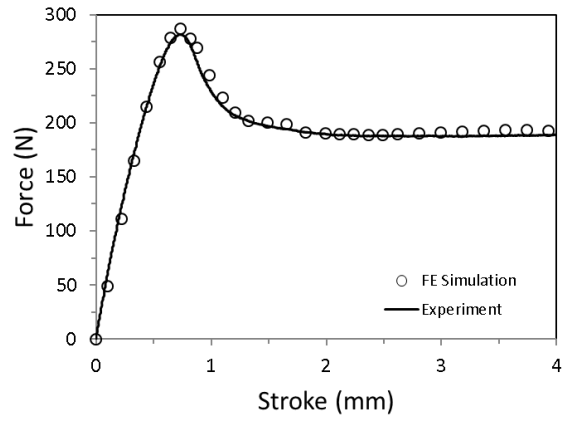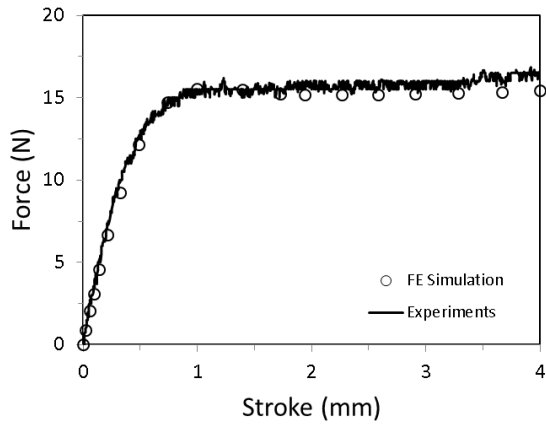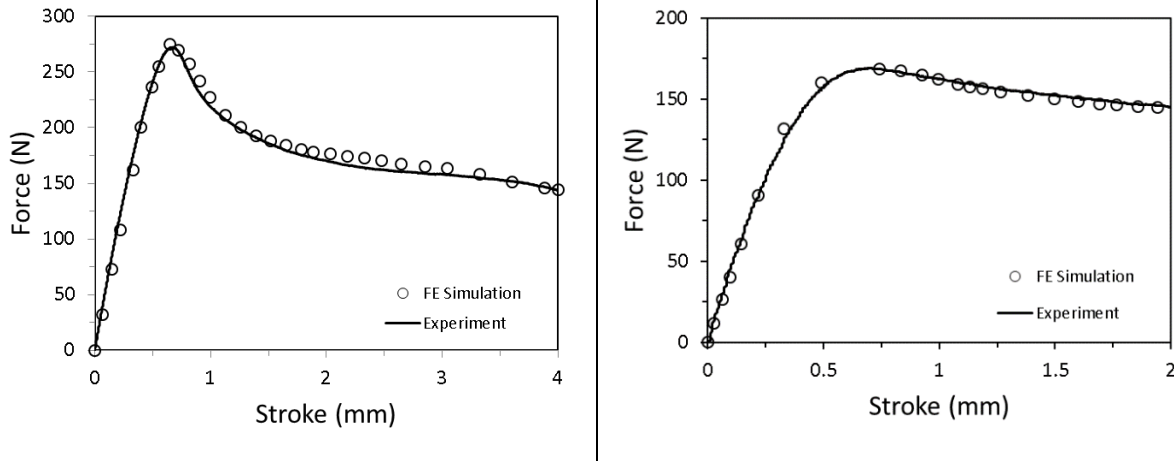
Figure 4-4 Force-stroke relations from FE models and from tensile test of CPVC dog-bone specimens with different treatments: (a)-(e) presents the specimens with the immersion treatment in acetone for 40 mins and for a drying period from 6 to 984 hours; (f)-(h) presents specimens with the immerison treatment in primer for 10 mins and for drying period from 96 to 984 hours.

The corresponding inputs equivalent stress-strain relations for the FE model are summarized in Figure 4-5 for cases immersion in acetone, and in Figure 4-7 for cases immersion in primer. Equivalent stress-strain relation of the virgin specimen presents a relatively obvious uplifting tail in the graph, which is realized by increasing the M value in Equation 4-4. The main difference in Equation 4-1 to Equation 4-4 for acetone-treated specimens with different drying periods of 312 and 984 hours is the value for M. Larger the M value, higher the rate of strain hardening to cross sectional reduction of the necked region [61]. This suggests that for those acetone-treated dog-bone specimens with the drying time from 312 to 984 hours, increase of the drying time still reduces transverse contraction in the gauge section, thus decreasing the ductility.

Equivalent stress for onset of necking in Figure 4-5 is plotted as a function of drying time in Figure 4-6, along with peak engineering stress from tensile tests. Figure 4-6 suggests a slight difference of equivalent stress for onset of necking for acetone-treated sheet specimens between drying for 312 hours and drying for 984 hours, in other word drying acetone-affected CPVC sheet specimen longer than 312 hours will not contribute much stress to resist necking.
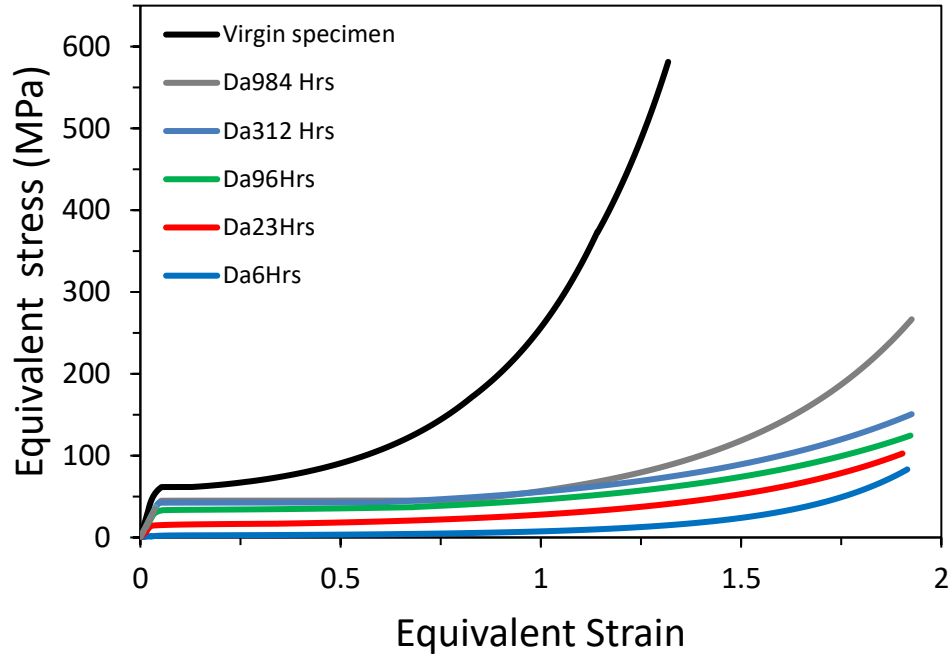
Figure 4-5 Equivalent stress for onset of necking in FE models and peak engineering stress in tensile tests of acetone-treated CPVC dog-bone specimens for 40 mins as a function of drying time.
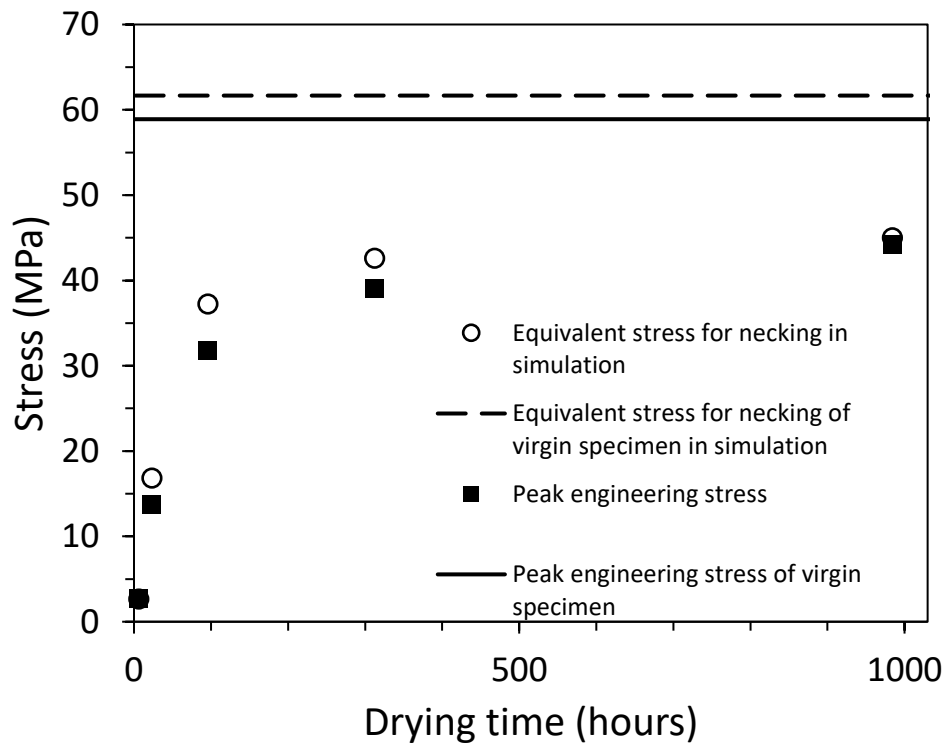
Figure 4-6 Collection of equivalent stress-strain relations of acetone treated CPVC dog-bone specimens and comparison to that of the virgin specimen.

58

Equivalent stress for onset of necking in Figure 4-7 is plotted as a function of drying time in Figure 4-8, along with peak engineering stress from tensile tests. Figure 4-8 suggests that the equivalent stress for onset of necking is nearly stabled for primer-treated sheet specimens after drying for 984 hours.

Figure 4-6 and Figure 4-8 also show that simulation to the equivalent stress before the onset of necking in simulation reasonably agree to the peak stress obtained from the experiment-determined engineering stress-stroke curve of chemical liquid treated CPVC sheet specimens.
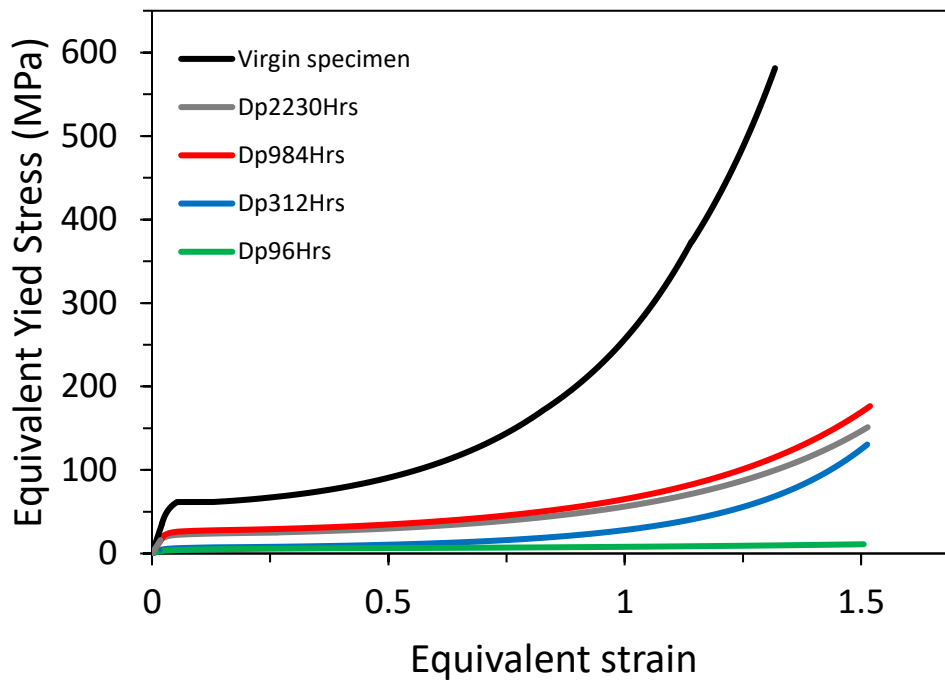
Figure 4-7 Equivalent stress for onset of necking in FE models and peak engineering stress in tensile tests of primer-treated CPVC dog-bone specimens for 10 mins as a function of drying time.
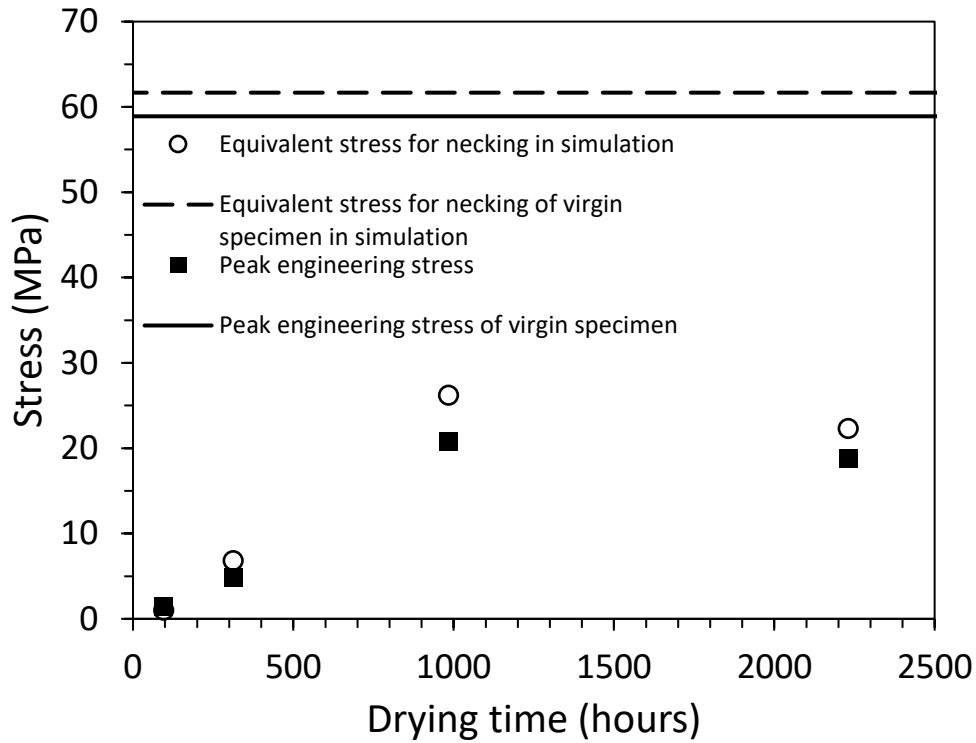
Figure 4-8 Collection of equivalent stress-strain relations of primer treated CPVC dog-bone specimens and comparison to that of the virgin specimen.

Values for parameters in the set of constitutive law for Equation 4-1 to Equation 4-4 are listed in Table 4-3, for acetone treated and primer treated specimens, respectively. The corresponding strain ranges for these constitutive equations are given in Table 4-5 and Table 4-6, for acetone and primer treatments, respectively.

Table 4-3 Value of parameters in the constitutive equations for FE models of acetone affected CPVC dog bone specimens. The number following 'A' indicates the drying time of specimens with a unit of hour.

		A6	A23	A96	A312	A984
Linear elastic in	E(MPa)	121	900	1500	1800	1770
Equation 4-1	ν	0.385	0.385	0.385	0.385	0.385
	a	7	1	7	4	10
Non-linear	b	0.01	0.02	0.02	0.02	0.02
deformation in	c	0.4	0.18	0.15	0.03	0.15
Equation 4-2	d	-1.8	-2.2	-4	-4	-15.7
	e	5.4	60	73.2	112	109

Hollomon's equation for plastic deformation in Equation 4-3	αk	6.66	35.6	69.3	85.4	90.2
	N	0.1	0.05	0.01	0.01	0.001
Strain hardening deformation in Equation 4-4	Section1 k	5.23	31.1	67.6	73.2	63
	Section1 M	1.1	0.6	0.2	0.45	0.6
	Section1 β	1.8	1.8	1.8	1.8	1.8
	Section2 k			60.5		59
	Section2 M	NA	NA	0.45	NA	0.7
	Section2 β			1.8		1.8

Table 4-4 Values of parameters in the constitutive equations for FE models of primer affected CPVC dog bone specimens. The number following 'P' indicates the drying time of specimens with a unit of hour.

		P96	P312	P984	P2230
Linear elastic in Equation 4-1	E(MPa)	168	483	1580	1640
	ν	0.385	0.385	0.385	0.385
Non-linear deformation in Equation 4-2	a	18	2.8	1.3	1.3
	b	0.02	0.02	0.01	0.01
	c	0.3	0.04	0.3	0.3
	d	-4	-0.5	-1.2	-1.2
	e	4.1	15	58.5	50.6
Hollomon's equation for plastic deformation in Equation 4-3	αk	7.6	20.4	62.05	54.5
	N	0.2	0.15	0.05	0.06
Strain hardening deformation in	Section1 k	5.97	14.4	54.8	46.95
	Section1 M	0.3	1.4	0.9	0.9
	Section1 β	1.8	1.8	1.8	1.8

Equation 4-4

Table 4-5 The strain range for constitutive equations governing the FE models of acetone affected CPVC dog bone specimens. The number following 'A' indicates the drying time of specimen in the unit of hour.

		A6	A23	A96	A312	A984
Linear elastic in Equation 4-1		0~0.025	0~0.013	0~0.035	0~0.036	0~0.036
Non-linear deformation in Equation 4-2		0.026~0.085	0.014~0.027	0.036~0.057	0.037~0.046	0.037~0.052
Hollomon's equation for plastic deformation in Equation 4-3		0.086~0.135	0.028~0.343	0.058~0.185	0.047~0.586	0.053~0.786
Strain hardening deformation in Equation 4-4	Section1	0.136~1.89	0.344~1.89	0.186~0.685	0.587~1.89	0.787~0.836
	Section2	NA	NA	0.686~1.89	NA	0.837~1.89

Table 4-6 The strain range for constitutive equations governing the FE models of primer affected CPVC dog bone specimens. The number following 'P' indicates the drying time of specimens in the unit of hour.

	P96	P312	P984	P2230
Linear elastic in Equation 4-1	0~0.0075	0~0.015	0~0.022	0~0.016
Non-linear deformation in Equation 4-2	0.0085~0.0275	0.016~0.083	0.023~0.056	0.017~0.051
Hollomon's equation for plastic deformation in Equation 4-3	0.0285~0.4075	0.084~0.135	0.057~0.172	0.052~0.266

Strain hardening deformation in Equation 4-4	Section1	0.4085~1.49	0.136~1.49	0.173~1.49	0.267~1.49

Young's modulus used for the FE models to mimic the CPVC dog bone specimens after the treatment by acetone or primer is summarized in Figure 4-9, together with the values for the virgin specimens.
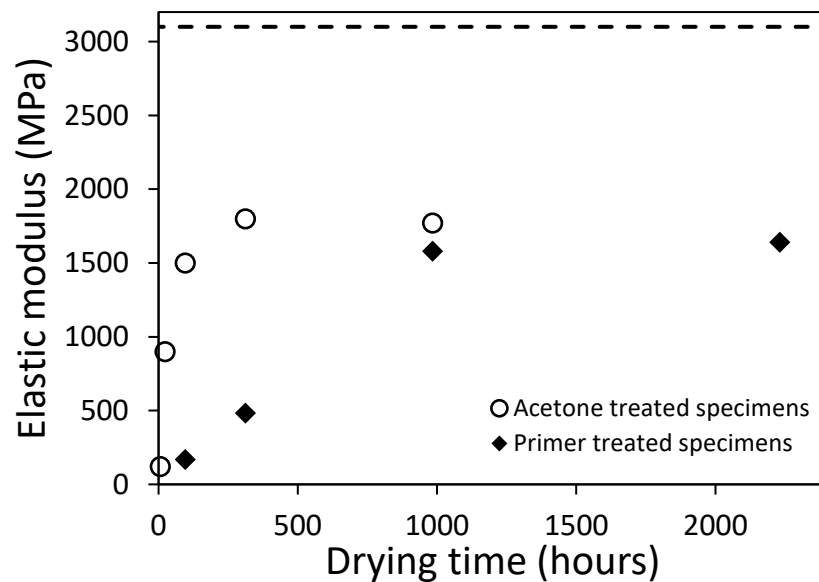
Figure 4-9 Collection of elastic modulus input into FE models. The dashed line represents the relative value of virgin specimen; Circles represents values for acetone treated specimens and squares is for primer treated specimens.

It is seen that recovery of elastic modulus for the acetone-treated specimens is faster than that for the primer-treated specimens, as the elastic modulus for the former increases dramatically in the beginning of the drying stage, and stops after drying for 312 hours. For primer treated specimens, the recovery is at a linear rate until the drying time is around 984 hours before a plateau is reached. Interestingly, both treatments, to either acetone or primer, the CPVC dog-bone specimens seems to eventually reach a plateau value for the elastic modulus that is much lower than the elastic modulus for the virgin

specimen. This may indicate that acetone plays key role in primer to affect stiffness of CPVC sheet. However, more tests are needed to examine influence of other ingredients in primer on the stiffness change of CPVC.

Chapter 5 Summary and future works

Main findings of the current work are summarized in this chapter, followed by some suggestions for future investigation.

5.1 Summary of current work

CPVC has been widely accepted by the industry as pipeline material, given the reliability and outstanding price-performance ratio. Although equipped with good capability of chemical resistance, primer-immersed CPVC pipe specimens were found suffered strength and ductility loss.

Based on that, this thesis conducted some detailed study and concluded that immersion in acetone, (the ingredient with the highest wt% in primer) would weaken the strength of extruded CPVC sheet specimen and a drying process for acetone or primer-treated sheet specimens for thousand hours could not fully recover the mechanical properties. The extruded CPVC pipe specimen with a similar treatment shows better strength recovery after drying process, possibly due to larger thickness of the pipe than the sheet, but ductility of the treated ring specimens is still reduced from the ductility of the virgin ring specimen from the pipe. This is different from the ductility decrease of sheet specimens in the drying process, as the ductility of the treated sheet specimens is always higher than the virgin specimen.

Premature fracture occurs to the CPVC ring specimens after immersion in or local exposure to acetone or primer. Crack was initiated on a solvent-affecting-zone (SAZ) for ring specimens that had a local contact to acetone or primer on the inner surface. Due to crack initiation and gradual propagation, it results in the early fracture. Therefore, chemical liquids should be carefully handled to avoid unnecessary contact with CPVC surface. Finally, it is suggested that the influence of chemical liquids on the ductility of CPVC material, especially in the pipe forms, should be carefully characterized to ensure the reliability of the material in the long-term service.

The main contributions of this thesis are summarized below.

1) Design a new fixture for 'wet' test of dog-bone specimens

Characterization to the resistance of plastics to chemical liquids requires to conduct tensile test to sheet specimen while it is being immersed in the chemical liquid. An in-house-designed of fixtures was established and manufactured to study mechanical property change of CPCV sheet during the immersion in acetone or primer.

2) Propose a concept for the premature fracture of CPVC pipe in contact with chemical liquids

Premature fracture of 2-inch CPVC specimens in the mechanical, after in contact with chemical liquids (acetone and primer) has been found, which shows a different trend from that shown in extruded 1/32" CPVC sheet specimens with a similar treatment.

Furthermore, experiments have been conducted to examine the ductility change of pipe due to local contact with chemical liquids. The results suggest that crack initiated from the chemical liquid affected zone is responsible for the premature fracture. This is the first time that experimental evidence is obtained to explain the brittle fracture of PVC and CPVC pipe materials that shorten their service life.

3) Determination of equivalent stress-strain relations of CPVC sheet with and without immersion treatment in chemical liquids

A phenomenological approach is successfully used to simulate the elastic-plastic deformation of CPCV dog-bone specimens to examine the influence of using chemical liquids on their stress-strain relationship. Creep deformation was found to have little influence on the stress-strain relationship determined from the tensile test of CPVC specimens.

The equivalent engineering stress-strain curve from the FE model reflects the different effect of acetone and primer on the mechanical property change of CPVC sheet specimens, and the role of drying time on the mechanical property recovery of these specimens.

5.2 Future work

Study in this thesis provides an idea about the failure mechanism that is responsible for premature fracture of CPVC pipe when contacting with chemical liquids. Given the complexity of this topic, future work is needed to verify the failure mechanism for the ring specimens prepared from different manufactures and in different batch. The future work could also be conducted to characterize the different level of premature fracture of CPVC pipe in contact with different chemical liquids. Detailed examination of the influence of local contact to primer on the brittle fracture of the ring specimen also needs further investigation.

The current work on the effect of immersion in acetone on the change of mechanical property for CPVC ring specimen is only focused on specimens after drying for up to 252 hours. Even though the results could support the idea proposed in this thesis, a series of tests with different length of drying time should be conducted in the future to verify the concept for the premature brittle fracture.

A study has been carried out using the constitutive model to estimate the elastic-plastic deformation of CPVC sheet specimens through correlating the mechanical property change with the exposure to chemical liquids. Further study is suggested to apply the knowledge obtained from the current work to simulate the mechanical performance of CPVC ring specimens in different loading modes, after being in contact with chemical liquids. Influence of variation in the 'shell' region of ring specimens could also be considered in the future work, to understand the effect of diffusion of the chemical liquids in CPVC pipe and their influence on its mechanical behavior.

Bibliography

[1]   Chasis, David A. Plastic Piping Systems. Industrial Press Inc., 1988.

[2]   Walsh, Thomas. "The Plastic Piping Industry in North America." In Applied Plastics Engineering Handbook, William Andrew Publishing, 2011.

[3]   Osten, K. F. "Plastic piping in gas distribution." Three R Int.;(Germany, Federal Republic of) 19, no. 10 (1980).

[4]   M. Mock Carroll, "Polyvinylchloride (PVC) pipe reliability and failure modes," Reliab. Eng., vol. 13, no. 1, pp. 11–21, Jan. 1985.

[5]   Korsman, H., S. De Boer, and I. Smits. "Cost benefits and long term behaviour of a new all plastic piping system." In Proceedings of the 11th International Symposium on District Heating and Cooling. 2008.

[6]   Cruz, Javier, Bruce Davis, Paul Gramann, and Antoine Rios. "A study of the freezing Phenomena in PVC and CPVC Pipe Systems." In ANTEC 2010 CONFERENCE PROCEEDINGS, 2010.

[7]   Heim, Timothy H., and Andrea M. Dietrich. "Sensory aspects and water quality impacts of chlorinated and chloraminated drinking water in contact with HDPE and cPVC pipe." Water research 41, no. 4 (2007): 757-764.

[8]   Mruk, S., H. F. Mark, N. M. Bikales, C. G. Overberger, G. Menges, and J. I. Kroschwitz. "Pipe. Encyclopedia of polymer science and technology." (1988).

[9]   Martins, Johnny De N., Estevão Freire, and Henry Hemadipour. "Applications and market of PVC for piping industry." Polímeros 19, no. 1 (2009): 58-62.

[10]   Yang, Fenglin, and Vladimir Hlavacek. "Improvement of PVC wearability by addition of additives." Powder technology 103, no. 2 (1999): 182-188.

[11]   Jia, Puyou, Lihong Hu, Xiaohui Yang, Meng Zhang, Qianqian Shang, and Yonghong Zhou. "Internally plasticized PVC materials via covalent attachment of aminated tung oil methyl ester." RSC advances 7, no. 48 (2017): 30101-30108.

[12] Pan, Siyu, Delong Hou, Jinming Chang, Zhou Xu, Songhang Wang, Sunxian Yan, Qi Zeng, Zhonghui Wang, and Yi Chen. "A potentially general approach to aliphatic ester-derived PVC plasticizers with suppressed migration as sustainable alternatives to DEHP." Green Chemistry 21, no. 23 (2019): 6430-6440.

[13] Lenartowicz, Marta, Beata Swinarew, Andrzej Swinarew, and Grażyna Rymarz. "The evaluation of long-term aged PVC." International Journal of Polymer Analysis and Characterization 19, no. 7 (2014): 611-624.

[14] Chemline Plastics, "Chemical resistance guide, ISO 9001:2015 CERTIFIED" 2015.

[15] Merah, Nesar, Farukh Saghir, Z. Khan, and A. Bazoune. "A study of frequency and temperature effects on fatigue crack growth resistance of CPVC." Engineering fracture mechanics 72, no. 11 (2005): 1691-1701.

[16] Knight, Michelle. "Chemical Resistance and Chemical Applications for CPVC pipe and fittings." Corzan Industrial Systems.

[17] Forsyth, D. S., and B. Jay. "Organotin leachates in drinking water from chlorinated poly (vinyl chloride)(CPVC) pipe." Applied Organometallic Chemistry 11, no. 7 (1997): 551-558.

[18] Hall, Christopher. Polymer materials: an introduction for technologists and scientists. Macmillan International Higher Education, 2017.

[19] Brockmann, Walter, Paul Ludwig Geiß, Jürgen Klingen, and Bernhard Schröder. "Adhesive Bonding as a Joining Technique." Adhesive Bonding: Materials, Applications and Technology (2009): 1-3.

[20] Matellan, Carlos, and E. Armando. "Cost-effective rapid prototyping and assembly of poly (methyl methacrylate) microfluidic devices." Scientific reports 8, no. 1 (2018): 1-13.

[21] Grewell, David, and Avraham Benatar. "Welding of plastics: fundamentals and new developments." International Polymer Processing 22, no. 1 (2007): 43-60.

[22]   P. Fittings, and V. Pipe, "Standard Practice for the Two-Step (Primer and Solvent Cement) Method of Joining Poly (Vinyl Chloride) (PVC) or Chlorinated Poly (Vinyl Chloride) (CPVC) Pipe and Piping Components with," vol. 96, no. January, pp. 1–10, 2016.

[23]   ASTM, "Standard Specification for Primers for Use in Solvent Cement Joints of Poly (Vinyl," Astm, vol. 08, no. October 2002, pp. 4–6, 2015.

[24]   C. P. Pipe, "Standard Specification for Solvent Cements for Chlorinated Poly (Vinyl Chloride)," Annu. B. ASTM Stand., vol. 08, pp. 1–7, 2004.

[25]   P. I. Vincent and S. Raha, "Influence of hydrogen bonding on crazing and cracking of amorphous thermoplastics," Polymer (Guildf)., vol. 13, no. 6, pp. 283–287, 1972.

[26]   D. Wright, Environmental stress cracking of plastics. 1996.

[27]   "ASTM D543 : Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents."

[28]   "ISO - ISO 22088-1:2006 - Plastics — Determination of resistance to environmental stress cracking (ESC) — Part 1: General guidance.".

[29]   B. Chen, P.-Y. Ben Jar, P. Mertiny, and R. Prybysh, "Strength and Ductility Loss of CPVC Pipe Due to Exposure to Primer," J. Press. Vessel Technol., vol. 142, no. 2, pp. 1–8, 2020.

[30]   Laiarinandrasana, Lucien, E. Gaudichet, S. Oberti, and Clémence Devilliers. "Effects of aging on the creep behaviour and residual lifetime assessment of polyvinyl chloride (PVC) pipes." International journal of pressure vessels and piping 88, no. 2-3 (2011): 99-108.

[31]   Rahman, Shah, and Reynold K. Watkins. "Longitudinal mechanics of buried thermoplastic pipe: Analysis of PVC pipes of various joint types." In Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy, pp. 1101-1116. 2005.

[32] Merah, N., A. Bazoune, A. Fazal, and Z. Khan. "Weathering degradation mechanisms of chlorinated PVC." International Journal of Plastics Technology 17, no. 2 (2013): 111-122.

[33] N. Merah, A. Bazoune, and Z. Khan, "Artificial and Natural Weathering of Chlorinated Polyvinyl Chloride (CPVC)," Trans Tech Publ, 2013.

[34] J. Rotheiser, "Joining of plastics: handbook for designers and engineers," 2015.

[35] "ASTM F402 - 18 Standard Practice for Safe Handling of Solvent Cements, Primers, and Cleaners Used for Joining Thermoplastic Pipe and Fittings."

[36] W. H. H. Company, "Safety data sheet Safety data sheet," pp. 2–7, 2011.

[37] Avantor, "Safety Data Sheet- Safety Data Sheet," Mater. Saf. Data Sheet, vol. 4, no. 2, pp. 8–10, 2012.

[38] S. Folkman, "Water Main Break Rates In the USA and Canada: A Comprehensive Study Overall Pipe Breaks Up 27% In Six Years," 2018.

[39] Knight, M.L, 2003, January. Failure analysis of PVC and CPVC piping materials. In CORROSION 2003. NACE International.

[40] L. S. Burn, "Effect of installation damage on the lifetime of upvc pipes subjected to cyclic pressures," Polym. Int., vol. 26, no. 3, pp. 147–150, 1991.

[41] D. Priddy, Why Do PVC & CPVC Pipes Occasionally Fail?. Plastic Failures Lab Midland, MI document.

[42] S. Gould, P. Davis, D. Beale, D. M.-E. F. Analysis, and undefined 2013, "Failure analysis of a PVC sewer pipeline by fractography and materials characterization," Elsevier.

[43] S. Singhal, V. Lohar, and V. Arora, "Hot melt extrusion technique," 2011.

[44] R. G. Wunderlich, R. H. Dalry, and R. R. Burn, "INSTRUMENTATION AND CONTROL.," Nucl. Eng. Int., vol. 19, no. 219, pp. 656–658, 1974.

[45] M. Xanthos and D. B. Todd, "Plastics Processing," in Kirk-Othmer Encyclopedia of Chemical Technology, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2003.

[46] M. Sauceau, J. Fages, A. Common, C. N.-P. in P., and undefined 2011, "New challenges in polymer foaming: A review of extrusion processes assisted by supercritical carbon dioxide," Elsevier.

[47] M. Moghri, H. Garmabi, and M. Akbarian, "Effect of processing parameters on fusion and mechanical properties of a twin-screw extruded rigid PVC pipe," J. Vinyl Addit. Technol., vol. 9, no. 2, pp. 81–89, Jun. 2003.

[48] W. V. Titow, "Extrusion," in PVC Plastics, Dordrecht: Springer Netherlands, 1990, pp. 497–523.

[49] W. V. Titow, M. Braden, B. R. Currell, and R. J. Loneragan, "Diffusion and some structural effects of two chlorinated hydrocarbon solvents in bisphenol A polycarbonate," J. Appl. Polym. Sci., vol. 18, no. 3, pp. 867–886, 1974.

[50] B. Chen, P.-Y. Ben Jar, P. Mertiny, and R. Prybysh. "Ductility Loss of CPVC Pipe Due to Exposure to Primer." Journal of Pressure Vessel Technology.

[51] M. Knight, Chemical Resistance and Chemical Applications for CPVC pipe and fittings. Corzan Industrial Systems.

[52] A. R. Book, Machinery ' s Handbook. .

[53] M. Tsige and G. S. Grest, "Molecular dynamics simulation of solvent-polymer interdiffusion: Fickian diffusion" J. Chem. Phys, vol. 120, no. 6, p. 2989, Feb. 2004.

[54] L.-X. Zhang et al., "Study of compatibility, morphology structure and mechanical properties of CPVC/ABS blends," J. Appl. Polym. Sci., vol. 116, no. 6, p. NA-NA, Jun. 2010.

[55] Z. Khan, N. Merah, and F. Saghi, "Fatigue crack growth process in CPVC pipe couplings," E-Polymers, no. 060, pp. 1–13, 2007.

[56] V. K. Khanna et al., Design and development of ion-sensitive field-effect transistor and extended-gate field-effect transistor platforms for chemical and biological sensors, vol. 14. 2014.

[57] J. C. Arnold, "The influence of liquid uptake on environmental stress cracking of glassy polymers," Mater. Sci. Eng. A, vol. 197, no. 1, pp. 119–124, Jun. 1995.

[58] Akovali, G. "Plastic materials: Chlorinated polyethylene (CPE), chlorinated polyvinylchloride (CPVC), chlorosulfonated polyethylene (CSPE) and polychloroprene rubber (CR)." In Toxicity of Building Materials, pp. 54-75. Woodhead Publishing, 2012.

[59] Hauser, Ray. "Environmental Stress Cracking of Commercial CPVC Pipes." In Plastic Pipe and Fittings: Past, Present, and Future. ASTM International, 2011.

[60] Kuliczkowska, Emilia, and Agata Zwierzchowska. "A qualitative analysis of early defects present in PVC-U sewers but not observed in rigid pipes." Tunnelling and Underground Space Technology 56 (2016): 202-210.

[61] Muhammad, S., and P-YB Jar. "Determining stress–strain relationship for necking in polymers based on macro deformation behavior." Finite Elements in Analysis and Design 70 (2013): 36-43.

[62] P. D. Wu and E. van der Giessen, "On neck propagation in amorphous glassy polymers under plane strain tension," Int. J. Plast., vol. 11, no. 3, pp. 211–235, Jan. 1995.

[63] B. D. Coleman, "Necking and drawing in polymeric fibers under tension," Arch. Ration. Mech. Anal., vol. 83, no. 2, pp. 115–137, Jun. 1983.

[64] J. W. Hutchinson and K. W. Neale, "Neck propagation," J. Mech. Phys. Solids, vol. 31, no. 5, pp. 405–426, Jan. 1983.

[65] K. W. Neale and P. Tugcu, "Analysis of necking and neck propagation in polymeric materials," J. Mech. Phys. Solids, vol. 33, no. 4, pp. 323–337, Jan. 1985.

[66] P. Tugcu and K. W. Neale, "Necking and neck propagation in polymeric materials under plane-strain tension," Int. J. Solids Struct., vol. 23, no. 7, pp. 1063–1085, 1987.

[67] Q. Z. Fang, T. J. Wang, H. G. Beom, and H. P. Zhao, "Rate-dependent large deformation behavior of PC/ABS," Polymer (Guildf)., vol. 50, no. 1, pp. 296–304, Jan. 2009.

[68] L. Fager, J. B.-I. journal of solids and structures, and undefined 1986, "Plane strain neck propagation," Elsevier.

[69] G. D. Dean, L. N. McCartney, R. Mera, and J. M. Urquhart, "Modeling nonlinear viscoelasticity in polymers for design using finite element analysis," Polym. Eng. Sci., vol. 51, no. 11, pp. 2210–2219, Nov. 2011.

[70] A. Muliana and K. R. Rajagopal, "Modeling the response of nonlinear viscoelastic biodegradable polymeric stents," Int. J. Solids Struct., vol. 49, no. 7–8, pp. 989–1000, Apr. 2012.

[71] F. Khan and C. Yeakle, "Experimental investigation and modeling of non-monotonic creep behavior in polymers," Int. J. Plast., vol. 27, no. 4, pp. 512–521, Apr. 2011.

[72] P. Tuğcu, K. N.-I. journal of mechanical sciences, and undefined 1987, "Analysis of plane-strain neck propagation in viscoplastic polymeric films," Elsevier.

[73] D. A. Şerban, L. Marşavina, and V. V. Silberschmidt, "Response of semi-crystalline thermoplastic polymers to dynamic loading: A finite element study," in Computational Materials Science, Nov. 2012, vol. 64, pp. 116–121.

[74] Kwon, H. J., and P-YB Jar. "On the application of FEM to deformation of high-density polyethylene." International Journal of Solids and Structures 45, no. 11-12 (2008): 3521-3543.

[75] Yoshihiro, Tomita, and Hayashi Kenichi. "Thermo-elasto-viscoplastic deformation of polymeric bars under tension." International journal of solids and structures 30, no. 2 (1993): 225-235.

[76] M. C. Boyce, D. M. Parks, and A. S. Argon, "Large inelastic deformation of glassy polymers. Part I: rate dependent constitutive model," 1988.

[77] J. J. Wu and C. P. Buckley, "Plastic deformation of glassy polystyrene: A unified model of yield and the role of chain length," J. Polym. Sci. Part B Polym. Phys., vol. 42, no. 11 SPEC. ISS., pp. 2027–2040, Jun. 2004.

[78] S. Muhammad and P. Y. B. Jar, "Effect of aspect ratio on large deformation and necking of polyethylene," J. Mater. Sci., vol. 46, no. 4, pp. 1110–1123, Feb. 2011.

[79] R. W. Armstrong and S. M. Walley, "High strain rate properties of metals and alloys," Taylor Fr., vol. 53, no. 3, pp. 105–128, May 2013.

[80] K. G. Hoge and A. K. Mukherjee, "The temperature and strain rate dependence of the flow stress of tantalum," J. Mater. Sci., vol. 12, no. 8, pp. 1666–1672, Aug. 1977.

APPENDIX

Dimensions of the standard O-rings used in the current work, pointed by red arrows.

Standard USA O-Rings Sizes

Dimensions per AS568 although tolerances vary by use. Thousands of non-standard sizes are available in stock or can be made within a few weeks typically without tooling fees so no need to settle for a less than optimal fit.
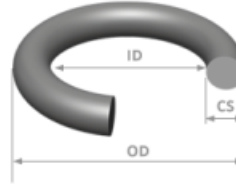
| Size	CS (IN)	ID (IN)	OD (IN)	CS (MM)	ID (MM)	OD (MM)
001	0.040	0.029	0.109	1.02	0.74	2.78
002	0.050	0.042	0.142	1.27	1.07	3.61
003	0.060	0.056	0.176	1.52	1.42	4.46
004	0.070	0.070	0.210	1.78	1.78	5.34
005	0.070	0.101	0.241	1.78	2.57	6.13
006	0.070	0.114	0.254	1.78	2.90	6.46
007	0.070	0.145	0.285	1.78	3.68	7.24
008	0.070	0.176	0.316	1.78	4.47	8.03
009	0.070	0.208	0.348	1.78	5.28	8.84
010	0.070	0.239	0.379	1.78	6.07	9.63
011	0.070	0.301	0.441	1.78	7.65	11.21
012	0.070	0.364	0.504	1.78	9.25	12.81
013	0.070	0.426	0.566	1.78	10.82	14.38
014	0.070	0.489	0.629	1.78	12.42	15.98
015	0.070	0.551	0.691	1.78	14.00	17.56
016	0.070	0.614	0.754	1.78	15.60	19.16
017	0.070	0.676	0.816	1.78	17.17	20.73
018	0.070	0.739	0.879	1.78	18.77	22.33
→ 019	0.070	0.801	0.941	1.78	20.35	23.91
020	0.070	0.864	1.004	1.78	21.95	25.51
021	0.070	0.926	1.066	1.78	23.52	27.08
022	0.070	0.989	1.129	1.78	25.12	28.68
023	0.070	1.051	1.191	1.78	26.70	30.26
024	0.070	1.114	1.254	1.78	28.30	31.86
025	0.070	1.176	1.316	1.78	29.87	33.43
026	0.070	1.239	1.379	1.78	31.47	35.03
027	0.070	1.301	1.441	1.78	33.05	36.61
028	0.070	1.364	1.504	1.78	34.65	38.21
029	0.070	1.489	1.629	1.78	37.82	41.38
030	0.070	1.614	1.754	1.78	41.00	44.56
031	0.070	1.739	1.879	1.78	44.17	47.73
→ 032	0.070	1.864	2.004	1.78	47.35	50.91
033	0.070	1.989	2.129	1.78	50.52	54.08

Detailed information of the in-house-designed fixtures.

ITEM NO.	PART NUMBER	Material	Key C operation to ITEM NO.	QTY.
1	89495K12 -McMASTER-CORR	304 Stainless Steel Round Tube	8; 11; 12	1
2	screw rod top	Stainless Steel	4	1
3	Top Cap_simple	ABS		3
4	Fixture Mount Top	Stainless Steel	14	1
5	Fixture Mount Bottom	Stainless Steel	10; 13	2
6	φ22.13_oring	Rubber_ASM-019	8	1
7	φ49.13_oring	Rubber_ASM-032	8	1
8	Bottom Clog	Stainless Steel		1
9	HNUT 0.5000-20-D-N	Standard Hex Nut		1
10	screw rod bottom	Stainless Steel		1
11	can cap	ABS		1
12	92196A341 -McMASTER-CORR	18-8 Stainless Steel Socket Head Screw		4
13	Clamp Block Bottom	Stainless Steel		1
14	Clamp Block Top	Stainless Steel		1
15	new specimen	CPVC		1
16	9157K14 -McMASTER-CORR	Standard Threaded Nipple Pipe		1
17	4114T21 -McMASTER-CORR	ON/OFF Ball Valve		1

77
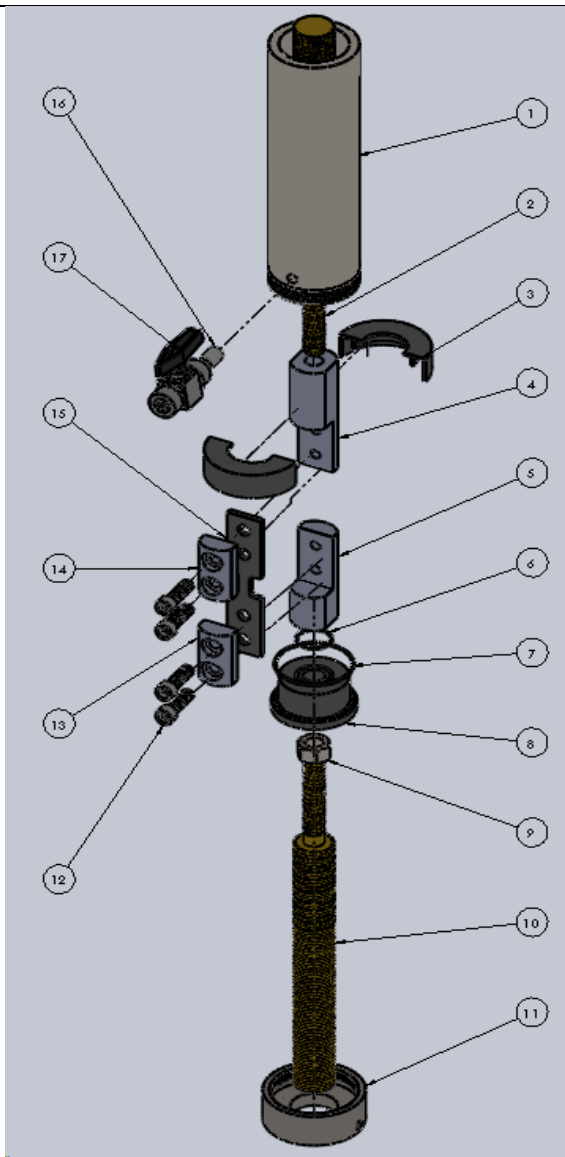
Collection of S_{fw} and σ_{eng_w} of CPVC sheet dog-bone specimens in 'Wet test' The number following 'W' is the length of time immersing in acetone in minutes.

	W0	W1.5	W5.4	W10.4	W15.3	W20.3
S_{fw}(mm)	1.96	3.57	4.92	5.91	6.78	7.01
σ_{eng_w}(MPa)	58.90	29.20	18.06	11.51	5.83	1.64

Collection of S_{fd1} and σ_{eng_d1} of CPVC sheet dog-bone specimens in 'Dry test' after treatment in acetone. "D0" represents the virgin CPVC dog-bone specimen. "--" indicates specimens have exceptional ductility. The number following 'Da' is the length of drying time in hours.

	D0	Da2.5	Da6	Da23	Da96	Da312	Da984
S_{fd1}(mm)	1.96	--	--	--	6.36	5.58	4.22
σ_{eng_d1} (MPa)	58.90	1.52	2.74	13.70	31.77	39.00	44.25
Initial slope(MPa/mm)	122.40	1.39	4.60	35.58	67.12	81.23	83.50
Recovery of yield strength	--	2.6%	4.7%	23.3%	53.9%	66.2%	75.1%
Recovery of initial slope	--	1.1%	3.8%	29.1%	54.8%	66.4%	68.2%

Collection of S_{fd2} and σ_{eng_d2} of CPVC sheet dog-bone specimens in 'Dry test' after treatment in primer. "D0" represents the virgin CPVC dog-bone specimen. "--" means specimens having outstanding ductility. The number following 'Dp' is the length of drying time in hours.

	D0	Dp96	Dp312	Dp984	Dp2230
S_{fd2}(mm)	1.96	--	--	5.57	5.52
σ_{eng_d2} (MPa)	58.90	2.09	5.66	20.25	18.81
Initial slope(MPa/mm)	122.40	4.65	15.98	57.93	55.86
Recovery of yield strength	--	3.5%	9.6%	34.4%	31.9%
Recovery of initial slope	--	3.8%	13.1%	47.3%	45.6%

Collection of S_{fr} and σ_{eng_r} of CPVC pipe ring specimens in 'Dry test'. 'V-R' represents the virgin ring specimen. Immersion in acetone (IMA), Immersion in primer (IMP), Local contact to acetone (LCA) or Local contact to primer (LCP) for different periods in hour(s); "--" means not applicable.Drying time for LCA is 10.5 days, and 10 days for LCP.)

	V-R	IMP0.5	IMA0.5	LCP2.5	LCA2.5
S_{fr}(mm)	18.33	5.73	8.08	1.37	11.86
σ_{eng_r}(MPa)	42.71	33.14	42.67	24.22	42.70
Initial slope(MPa/mm)	22.64	21.44	22.37	22.31	22.63
Recovery of ductility	--	31.3%	44.1%	7.5%	64.7%
Recovery of yield strength	--	77.6%	99.9%	56.71%	99.9%
Recovery of initial slope	--	94.7%	98.8%	98.5%	99.9%

Other attempts to have ring specimens with a local contact to chemical liquid.

Matlab codes to curve-fit the yield strength change of acetone-treated dog-bone specimens as a function of drying time on the logarithmic scale.

Input experimental data of yield strength

```
logoftime = [1.361727836,1.981138783,2.494154594,2.992995098];
yieldstresses = [13.7,31.77,39,44.245];
plot(logoftime,yieldstresses,"ok")
box off

line([35,35],[0,60],'color','k');
line([0,35],[60,60],'color','k');
```

Determine the value of parameters

```
constant = lsqcurvefit(@func,[1.5;1;0.04;21],yieldstresses,logoftime)
a =constant(1)
b=constant(2)
c=constant(3)
d=constant(4)
```

Plot on the same graph

```
xfit=0:0.5:52;
yfit = func(constant,xfit);

hold on
plot(yfit,xfit,"k","LineWidth",1.5)
plot([0,35],[58.85,58.85],"linewidth",1.5)
hold off
```

Matlab codes to curve-fit the initial slope change of acetone-treated dog-bone specimens as a function of drying time on the logarithmic scale.

Input experimental data of initial slpoe

```
logoftime = [1.361727836,1.981138783,2.494154594,2.992995098];
initialslopes = [35.58 67.12 81.23 83.504];
initialslopes = initialslopes';
plot(logoftime,initialslopes,"ok")
box off

line([50,50],[0,140],'color','k');
line([0,100],[140,140],'color','k');
```

Determine the value of parameters

```
constant = lsqcurvefit(@func1,[1.5;2;0.004;41],initialslopes,logoftime)
a = constant(1)
b = constant(2)
c = constant(3)
d = constant(4)
```

Plot on the same graph

```
xfit=0:0.5:90
yfit = func1(constant,xfit)

hold on
plot(yfit,xfit,"k","LineWidth",1.5)
plot([0,42],[122.4,122.4],"linewidth",1.5)
hold off
```