THE ANALYSIS OF POLYMER PIPE BEHAVIOUR IN FIRE CONDITIONS

Timothy William Marsden

Bachelor of Engineering
With a Major In Mechanical Engineering

MACQUARIE
University
SYDNEY·AUSTRALIA

Department of Mechanical Engineering
Macquarie University

November 7, 2016

Supervisor: Dr. Candace Lang
Co-Supervisor: Dr. Nicholas Tse

ACKNOWLEDGMENTS

I would like to acknowledge the time given to me by Professor Candace Lang for always having time for my questions and helping me throughout the process. As well, thank you to Martin Stirling from Hilti, my industry partner, who really helped me get the ball rolling for my project. Thanks to the gentleman at Tilecraft Crows Nest for supplying refractory tiles. Thank you to everyone who supported me through my project and devoted your time unselfishly.

STATEMENT OF CANDIDATE

I, Timothy William Marsden, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

Student's Name: Timothy William Marsden

Student's Signature:

Date: 7/11/2016

ABSTRACT

This report investigate the properties of polymer pipes of varying materials and their performance in high temperature compression testing. The inherent appeal of pipes, being the ease of manufacturing and implementation is also their downfall as polymers are adversely effected by heat. This becomes a major issue when they are implemented instead of metal pipes in fire conditions.

With the tendency for polymers to melt away in high temperatures, Hilti has developed products with aim to address this issue through the implementation of intumescent materials. The presence of this intumescent material in firestop products takes the heat induced swelling characteristic of the material to crush the polymer pipes it surrounds and prevent fire and smoke spread from what would be a gapping installation hole. These intumescent materials are activated at temperatures of over 180°C but little is known about how the polymer pipe is effected by this radial compression under those high temperature conditions due to the expensive and wasteful current testing methods.

The procedure developed in this report acts as a building block for future development in this area by successfully designing a diametral compression test for polymer pipes. This is then extended on to be applied to a designed and purpose built high temperature testing rig allowing for the production of high temperature results for a range of polymer pipes gaining the first results of their kind for this new area of research and investigation.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Subject

The introduction of polymer pipes into the building industry on a whole over the past fifty years has happened very quickly. This is primarily due to the immense benefits of polymer materials over its predecessors, metals. Plastic pipes overall tend to be cheaper to produce, easier to implement and kinder to the environment as a result of their manufacturing processes.

Although there is a trend towards the use plastic pipes the downsides of polymer properties must also be considered, primarily there susceptibility to high temperatures. This property is favourable in the manufacturing process allowing them to be shaped and manipulated, but when installed in fire proof rooms it can be detrimental to this quality of the room. When thermoplastic polymers reach high temperatures they melt away, much like those that would be experienced in building fires. When melted away the installation holes produce an avenue for the spread of smoke and flames, making the fireproof properties of the rest of the room redundant.

In a means to address this problem Hilti has developed a number of firestop products using the favourable properties on intumescent materials. These materials swell under high temperature and create multi-cellular fire resistant char that when implemented correctly can act as a "plug" to prevent spread of fires. However little is known about how these conditions of high temperatures and compression are experienced by the pipe as current testing methods are environmentally wasteful as well as being very expensive to undertake. This project aims to develop a test method that allows for the mimicking of the diametric compression the pipe would experience from being surrounded by intumescent materials in high temperature conditions of approximately 180°C.

1.2 Objectives

The objectives of this report are:

- Undertake initial diametral crush testing of a variety of polymer pipes to establish a set test method for reliable production of data for compression tests,
- Use the defined test method to produce data that will allow for stiffness characteristics of polymer pipes to be developed,
- Through testing, design a rig that will allow for high temperature compression testing of polymer pipes,
- Construct the designed high temperature testing rig,
- Undertake high temperature testing using the rig on the same polymer pipe types and compare load requirements to crush the pipes.

1.3 Limitations

1.3.1 Time

Due to the time constraints of this project, an amount of high temperature testing that would allow for an in-depth analysis of material properties is unlikely.

1.3.2 Materials

The range of pipe material that is being used is only a small area of the market that has been selected to try and meet the broadest range of characteristics in the market i.e. wall thickness, service temperature, overall strength and nominal diameters.

1.3.3 Cost

The report has a set limit of spending and as a result will limit the complexities of the testing and the rig design.

1.4 Plan Of Development

The report initially establishes a testing procedure for the various chosen polymer pipes and displays the results for the various dimensions of the pipes.

The results once analysed stood as control values for the design of a testing procedure to mimic the temperature features of building fires in a room.

This design was then means tested and once deemed effective through results analysis was constructing and used to high temperature test.

These results were then compared with that of the room temperature compression tests and scutenised to determine succesfulness of the designed rig.

Chapter 2

Literature Review

2.1 Plastic Piping Development

The introduction of polymer piping to the building industry to replace the previously used metals has resulted in the need for adaption to safety across a variety areas. The source of change to plastic came about due to immense benefits in environmental, financial and health aspects. A case study primarily focusing on the environmental and financial analysis highlighted the benefits from introduction of crosslinked polyethene (PEX) instead of copper in residential building water piping. It was shown that the introduction reduced the total costs of the building by 63% and reduced the carbon dioxide emissions by approximately 42% [12].

It was also noted that the introduction of plastic pipes addressed the health and performance issues that came about from long term use of metal piping. When looking at copper and lead pipes it was noted that as the pipes started to deteriorate over long periods the water flowing though pipes gained a metallic flavour as well as, in rare circumstances, made the water toxic [13,14]. As well as this, oxidisation within the metal pipes resulted in build-up on the internal walls of the pipe affecting the flow performance in the pipes as well as external surface rust that can cause performance issues with in the pipes such as leaks, water discoloration and blockages [15].

Although most of the examples above specifically refer to use in water transportation, other areas such as gas transport and electrical wire coverage most be considered also. The benefit of polymer pipes over metal is almost entirely related to the affordability of products whilst also being light weight and easily manipulated appealing to consumers.

The introduction of polymer pipes into the building industry happened very swiftly due to the previously mentioned benefits. The immense cost difference between the two materials was just so appealing in construction along with the other features, but safety needs to be a consideration especially surrounding the properties that metal have that plastics dont, specifically those relating to high temperatures.

2.2 Polymers

2.2.1 Production

Polymers come about in the production process called polymerisation, whereby links are made between single material molecules (e.g. vinyl chloride, ethene), called monomers, into long polymer chains made up of hundreds of thousands of those monomers. This simple process is called addition polymerisation, where open ends of chain are linked to the ends of other open ends with the help of a catalyst [16].

As a result of the simplicity of polymerisation along with the affordability of the base products, polymers are very cheap to produce therefore making the polymer pipes very financially appealing.

Due to the molecular structure of the material, a range of properties can be easily produced depending on how the chains are arranged or interlocked. Along with this, depending on which initial material is used in the polymerisation process the base characteristics, such as molecular weight, produces different polymer pipe properties.

2.2.2 Thermosets

During the polymerisation process the chains can be tangled through a mix of chemical forming process and high temperatures producing thermosets. Due to the strong chemical bonds brought about from this process thermosets have a strong resilience to high temperatures, tending to burn instead of melt in those conditions. As a result of this, once formed in the initial process, the polymer cannot be remoulded [17].

2.2.3 Thermoplastics

In the case of thermoplastics the chains are only weakly bonded to other chains meaning that when exposed to heat the chains are able to move about and, as a result, melt instead of burn. At room temperature these polymer chains are intertwined giving strength and form to the material. Thermoplastic properties can vary based on their chemical makeup and which polymer materials are used to make the chains [17].

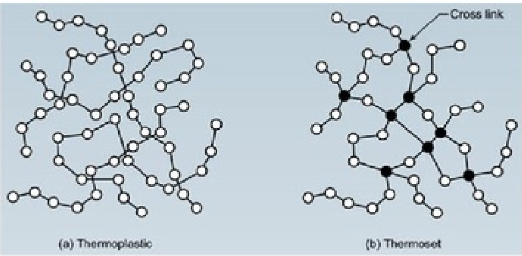


Figure 2.1: Molecular Structure of Thermosets vs Thermoplastics [1]

Once the thermoplastics are formed they are cooled to room temperatures from the high temperature that occur at the manufacturing stage and broken down into pellets or powder. To produce pipes, these pellets are feed into a machine, heated to become workable and then forced through a circular mould (die). This is called an extrusion, in which the thermoplastic is continuously moulded to a required length and simultaneously cooled resulting in a rigid plastic pipe [18].

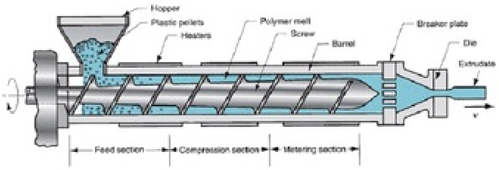


Figure 2.2: Polymer Pellets to Extrusion [2]

The low melting point of thermoplastics allows for easy variety in production shapes, sizes and wall thicknesses in pipes giving a huge versatility in use. As a result polymer pipes are used in a large portion of buildings for water, gas, sewage and many other areas.

2.2.4 Polymers in Fire Proof Installations

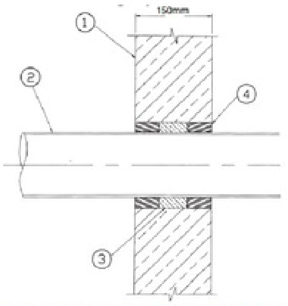
As mentioned in the previous section, thermoplastic polymer pipes can be used in a very wide variety of applications due to the materials versatility in manufacturing. Most of these applications occur in the construction industry where the pipes are used as a medium to carry things, such as cables or water etc., safely through divides such as walls, ceilings and floors.

The initial installation of these pipe involves an installation hole for the pipe to travel through the wall [18]. Now if this room needed to be fireproof, the walls would be constructed and manufactured to prevent fire or smoke from passing through them by having a specific fire resistance level (FRL), and in previous decades, in which metal pipes were used, there would be no issues as the metal would stay in place throughout the high temperatures due to its equally high FRL. However, due to the ever increasing use of polymer pipes, with their lower FRL, as a replacement, this leaves the fire proof walls susceptible to penetration via the installation holes through the melting away of the polymer pipes [19].

2.3 Hilti Firestop Products

2.3.1 Building Regulations

Due to the aforementioned properties of polymers and their quick introduction into the building industry, a large number of concerns arose regarding building elements with a



1. Wall: Concrete, blockwork, CSR™ Hebel® or masonry, 150mm thick
2. Plastic pipe of varying material, diameter & wall thicknesses:

Pipe type	Nominal Pipe Diameter	Nominal Pipe Wall thickness	Collar size	FRL Rating
PVC	32mm	1.9mm	CP 643 50/1.5" N	-/240/240
PVC	40mm	2mm	CP 643 50/1.5" N	-/240/240
PVC	50mm	2.2mm	CP 643 63/2" N	-/240/240
PVC	65mm	2.7mm	CP 643 75/2.5" N	-/240/240
PVC	80mm	2.9mm	CP 643 90/3" N	-/240/240
PVC	100mm	3.2mm	CP 643 110/4" N	-/240/240
PVC	150mm	4.5mm	CP 643 160/6" N	-/240/240
PE	50mm	2.9mm	CP 643 50/1.5" N	-/240/240
PE	63mm	2.7-4.0mm	CP 643 63/2" N	-/240/240
PE	75mm	2.7-4.0mm	CP 643 75/2.5" N	-/240/240
PE	90mm	2.7-4.0mm	CP 643 90/3" N	-/240/240
PE	110mm	2.7mm	CP 643 110/4" N	-/240/240
PE	160mm	4mm	CP 643 160/6" N	-/240/240

3. Mortar in fill
4. CP 643-N Firestop Jacket installed on both sides of the wall,recessed into the wall & flush with wall surfaces. Any gaps on exposed face can be sealed with CP 606 Fire Resistant Joint Filler.

Hilti (Aust) Pty Ltd
23 Egerton Street
Silverwater NSW 2128
Tel: 131 292
Fax: (02) 8748 1191

Figure 2.3: Installation of Firestop Collar Around a Ploymer Pipe [3]

required Fire Resistance Level (FRL) being penetrated by materials with a lower FRL and therefore building risk of spread of fire between fire compartments in buildings. This lead to changes of the Building Codes in Australia [3].

2.3.2 Firestop

Hilti, as a multinational company in construction tool design and engineering, identified the need of addressing the threat to fire proofing that thermoplastic pipes posed. From this, a variety of products were developed through the implementation of intumescent materials. These products are specifically designed to crush the material that it surrounds, through the implementation in fireproofing construction of collars, sleeves, wraps, etc., keeping the room fireproof while still being able to be constructed with polymer pipes [16].

The Building Code of Australia sets out the requirements that must be met during the construction process. Hilti must then design their products to meet these requirements for them to be allowable in the market. The following table shows an example of the building requirements and the Hilti interpretation of the requirements in their equipment design [20].

As displayed above, depending on the situation a specific type of firestop product is to be used and to specific requirements set out by building standards. The following table shows the current range of Hilti products that meet the multitude of standards. Note the

Building Code of Australia	Hilti Interpretation
If a pipe penetrates a hollow wall (such as a stud, a cavity wall or a hollow block-work) or a hollow floor/ceiling system, the cavity must be so framed and packed with fire-stopping material that the materials is	Penetrations shall be protected by a system that has been tested in accordance with AS4072.1-1992 and AS1530.4-1997. (Australian Standards)
(i) installed to a thickness of 25mm all around the service and of the wall, floor or ceiling. (ii) restrained independently of the service, from moving or parting from the surfaces of the service and of the wall, floor or ceiling	The installed fire stopping material or materials must-replicate the tested system and achieve an FRL of not less than that of the penetrated floor/wall/ceiling assembly The installed fire stopping material must replicate the tested system and achieve an FRL of not less than that of the penetrated surface assembly, in addition the fire stopping must be installed to a thickness of at least 25mm and independently restrained with the hollow construction.

Table 2.1: Building Code Requirements Example

requirement of all the products to crush the material it surrounds.

The main form of testing that is to be undertaken is that that replicates the collar firestop product (CP644) as it activates at a low temperature and crushes in a specific direction and over a specific length of the pipe. These characteristics are important in testing as the polymer is likely to have the most resistance to crush when it is close to its preferred operating temperatures, the crush type is easy to replicate on polymers in a controlled and repeatable manner and the defined length of material by its width results in material length being a defining test characteristic [18].

2.3.3 Intumescent Material

The crush testing that is going to be undertaken in this project is meant to loosely replicate the conditions that the polymer pipes are to experience during the intumescent material fire stop process. The intumescent materials expand when they are exposed to high temperatures (approximately 180°C and above) via an endothermic reaction. This expansion pushes in both directions but can be directed depending on its implementation [16, 21–23]. In the case of an installation hole, a collar placed around the pipe would be forced inwards because of the force of the collar external wall surrounding the material preventing its expansion outwards.

The particular type of intumescent used in these collars are called hard char intumescent. The application of this specific intumescent is due to the high expansion pressures produced from this type of intumescent that are required to crush the penetrating pipe and create an insulating char which limits the heat transfer and stops spread of flames [16].

Product	Material Makeup	Expansion Temperature
CP680 N	Expanding graphite embedded in a polyethylene matrix	180°C
CP644	An elastic intumescent made of foaming graphite in an acrylic matrix	180°C (Acts at low temp for a long period of time to allow for various strengths and thicknesses of pipes to be crushed)
CP 657	Foamed polyurethane (Contains Graphite)	300°C
CP 658	Two component polyurethane foam (Contains Graphite)	300°C
CP651 N	A mix of foaming graphite with vermiculite to provide a double intumescent reaction	Initially at 180°C and then at 600°C
CP611A	An expandable graphite in an acrylic dispersion with flame retarding additives	220°C
CP660	Two part polyurethane foam made by the reaction between polyol, water and polyisocyanate, mixed as applied through two foil packs	250°C

Figure 2.4: Current Hilti Firestop Products

The crush pressures produced from the intumescents in caused by a chemical change in graphites that occurs from flames, forming expanding bubbles that harden in to dense, heat insulating multi-cellular char [21].

2.4 Testing Materials

The chosen testing materials, Crosslinked Polyethene (PEX), Polyvinyl Chloride (PVC), High Density Polyethene (HDPE) and PEX-Al-PEX are done so as they cover the broadest range of properties.

2.4.1 High Density Polyethene Pipe

High Density Polyethene, or HDPE, is an ethene gas that is put under various pressure and temperature ranges as well as the addition of an aluminium catalyst, to produce a long, straight chain of molecules making the material very stiff due to their close proximity [24].

The manufactures of HDPE produce the base product for moulding in the forms of pellets much like the other previously mentioned pipe type materials. These pellets are then fed into a machine which, in turn, feeds them through a channel of heaters, melting them down and through pressure, forces them through a die of certain diameter and wall thickness based on material properties and pipe function. The standard max operating temperature is 80°C and has a shore hardness of 63 [25].

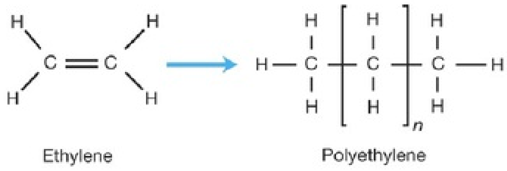


Figure 2.5: HDPE Molecular Structure [4]

2.4.2 Crosslinked Polyethene

Crosslinked Polyethene, better known as PEX, is polyethene material in which the polymer chains within the plastic have been linked through a secondary process. There are three different processes that can be used to do this:

- Peroxide (PEXa) and Silane (PEXb): both of which are chemical agents, peroxide causing the generation of free radicals and silane creating grafts, which form cross links in chains.
- Radiation (PEXc): where high energy creates the free radical to connect chains. Crosslinking of polyethylene into PEX for pipes results in increased, environmental stress crack resistance (ESCR), impact strength as well as improving the dimensional stability at elevated temperatures, therefore increasing operating temperatures to approximately 82°C and a Shore hardness of 55-63. PEX pipes also tend to have thicker walls to meet the pressure requirements of the applications of the pipe such as gas or water transport [5, 26].

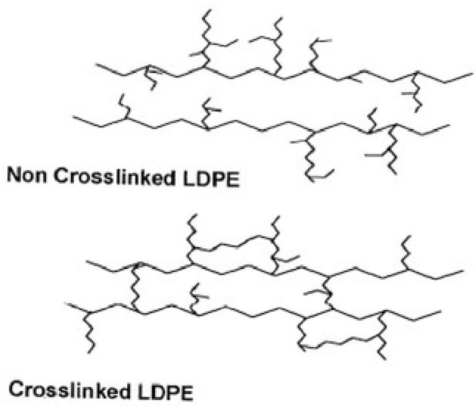


Figure 2.6: Crosslinked vs Non Crosslinked PE [5]

2.4.3 Polyvinyl Chloride

Polyvinyl Chloride, mostly referred to as PVC, is polymer of vinyl chloride chained molecules and as a result is hard, rigid and resistant to most chemicals with a Shore hardness of 80. It can be used at temperatures below 60°C, however its temperature limit is dependent on stress and environmental conditions [27, 28]. PVC pipe is produced through extrusion much like PEX and is heavily used in construction for plumbing and the protection of electric wires.

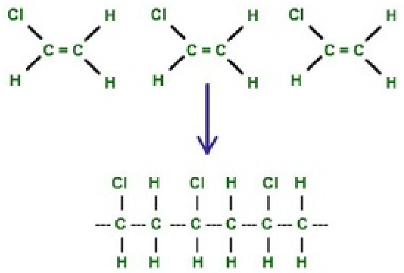


Figure 2.7: PVC Moleculer Polimerisation [6]

2.4.4 PEX AL PEX

PEX-Al-PEX is a composite pipe structure consisting of layers of both PEX and aluminium. The inner layer of the pipe is PEX allowing the pipe to be used for a variety of purposes including both water and gas. Following that a layer of longitudinally butt-welded aluminium is wrapped around the pipe during the extrusion process. An external layer of PEX is also present to prevent on the exterior to provide shock-resistance and protect the aluminium layer from being damaged from external contact to the elements. During manufacturing the plastic pipe is extruded with thin layer of aluminium feed into and through the die simultaneously meaning both layers are forced around either side of the aluminium [29, 30].

This type of pipe is usually used in gas transport due to the pipes ability to withstand high pressures by the addition of the aluminium layer.

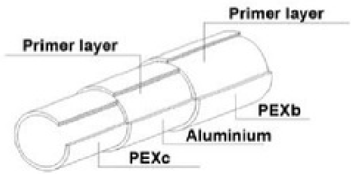


Figure 2.8: PEX AL PEX Material Layering [34]

2.5 Procedure Defined By Standards

2.5.1 Required Standards Documents

The standards to be used for the testing procedure are a product of ASTM. The Standard Test Method to be used:

- D2412 11 Determination of External Loading Characteristics of Plastic Pies Pipe by Parallel-Plate Loading [31]
- D2122 15 Determining Dimensions of Thermoplastic Pipe and Fittings [32]

Along with Standard Terminology Relating to:

- F412 16 Plastic Piping Systems [33]

2.5.2 Required Terminology

Relevant Terminology is defined by F412 16 Terminology Relating to Plastic Piping Systems [32]. These include:

- initial inside diameter (d)the average of the inside diameters as determined for the several test specimens and expressed in millimetres.
- load (F)the load applied to the pipe to produce a given percentage deection. Expressed as newtons per metre
- mean radius (r)the mid-wall radius determined by subtracting the average wall thickness from the average outside diameter and dividing the difference by two. Expressed as millimetres.
- pipe deection (stiffness) (P)the ratio of the reduction in pipe inside diameter to the initial inside diameter expressed as the percentage of the initial inside diameter
- liner cracking or crazingthe occurrence of a break or network of ne breaks in the liner visible to the unaided eye
- rupturea crack or break extending entirely or partly through the pipe wall.
- wall crackingthe occurrence of a break in the pipe wall visible to the unaided eye.
- wall delaminationthe occurrence of any separation in the components of the pipe wall visible to the unaided eye.
- pipe stiffness (PS)the value obtained by dividing the force per unit length of specimen by the resulting deection in the same units at the prescribed percentage deection
- stiffness factor (SF)the product of pipe stiffness and the quantity 0.149 r3 [32]

2.5.3 Standards for Testing

D2412 11 Determination of External Loading Characteristics of Plastic Pies Pipe by Parallel-Plate Loading is a test method that covers the determination of load-deflection characteristics of plastic pipes under parallel plate loading. The external loading properties of plastic pipes obtained from these standards include:

- Stiffness of the pipe
- Load-deflection characteristics
- Compare characteristics of various plastics in pipe form
- Study interrelations of dimensions and deflection properties of plastic pipe
- Measure the deflection and load-resistance at any of several significance events if they occur during the test

2.5.4 Instron Universal Tester

The machinery used to undertake the testing is an Instron Floor Model Testing System, allowing for the tensile and compression testing of materials. This system uses a company specific software called Bluehill 3 which allows for testing design and specifications.

This testing apparatus meets the ASTM testing standards being a machine that is a properly calibrated testing machine of the constant-rate-of-crosshead movement type meeting the requirements of Test Method D695.[26]

The machine has two parallel platens which meets the set out apparatus requirements. The load shall be applied to the specimen through two parallel steel bearing plates. The plates shall be at, smooth, and clean. The thickness of the plates shall be sufficient so that no bending or deformation occurs during the test, but it shall not be less than 6.0 mm. The plate length shall equal or exceed the specimen length and the plate width shall not be less than the pipe contact width at maximum pipe deection plus 150 mm. [31]

During the test the Universal Tester produces real-time graphs, test results and statistics available for viewing whilst testing. The change in inside diameter, or deformation parallel to the direction of loading, shall be measured with a suitable instrument meeting the requirements of Test Method D695, except that the instrument shall be accurate to the nearest 0.25 mm. The instrument shall not support the pipe test specimen or the plate or affect in any way the load deection measurements. Changes in diameter are measured during loading by continuously recording plate travel or by periodically computing it. [31]

The live plots produced by the Instron Universal Tester come in the form of Load (N) i.e. force exhibited on the test piece, vs extension (mm) i.e. the extension of the upper platen from its initial position. However, the raw data outputs in the form of progression of the test over time in 0.1 second increments, taking a load and extension measurement at that equivalent time. This data can once again be plotted in to a load vs extension or can also be manipulated in to a stress vs strain plot.

2.5.5 Stress vs Strain Analysis

As mentioned in the previous section, the Intron Universal Tester produces three forms of raw data, time (s) progression of the test, as well as the instantaneous load and extension measurements. However, when comparing test pieces with different dimensions such as length, wall thickness and diameters, plotting this data does not give a good comparative representation of strength. By introducing stress vs strain plots a comparison can be made as cross sectional area and initial diameters are taken into consideration.

The engineering stress:

$$\sigma_e = \frac{F}{A_0}[Pa] \tag{2.1}$$

incorporates the cross sectional area of the test piece and, in the situation of a pipe, is calculated using the formula:

$$A_0 = l(d_0 - d_i)[m^2] \tag{2.2}$$

where l is the length of the test piece within the bounds of the compression platen, and d_0 and d_i are the outer and inner diameter of the pipe respectively. When applying this to the raw data produced by the Instron Universal Tester, the load is placed over this cross-sectional area to produce the test pieces instantaneous engineering stress. The strain ϵ_e of a material in the case of compression testing, is a ratio of the initial height and the instantaneous change in height at a point in time within the test. This is therefore a dimensionless value and can be calculated as follows:

$$\epsilon_e = \frac{\delta}{L_0} \tag{2.3}$$

where δ is the instantaneous change in internal dimeter and L_0 is the initial internal diameter of the piece [34].

Manipulating the raw data produced coupled with the dimensions taken pre-testing using the equations above, a plot can be produced that will allow for comparison of different dimensioned test pieces and give a true measure of stiffness between the various material types.

The benefit of a plotted stress strain graph is the ability to identify and compare various stages within the compression test, such as the elastic and plastic phases of compression. Elasticity is the property of immediate recovery from an external displacement to its initial shape once the load is removed. Plastic deformation is a development of this principle where by the force is so great that a permanent change occurs to the materials form via a larger forced. So much that once the force is released the piece will hold its shape [34].

Identifying these areas in the plots of stress vs strain are somewhat subjective but usually follow a standard process. From the start of the test to the max load in the ramp up stage before any down turn or plateauing of the line is deemed the elastic phase with the max load being the elastic limit. The plastic phase of the test is anything that follows that, in which the compression changes the physical properties of the material on a molecular level, usually by the breaking of internal bonds, hence the inability for the substance to return to its original shape once the force is removed.

2.5.6 Calculations Defined by Standards

As defined by the standards document D2421-11 the following equations define pipe characteristics [31].

Calculate the pipe stiffness, PS, for any given deflections follows:

$$PS = \frac{F}{\Delta_y}[Pa] \tag{2.4}$$

When required, calculate the stiffness factor, SF, for any given deflection as follows:

$$SF = 0.149r^3 * PS \tag{2.5}$$

When required, calculate the percentage pipe deflection, P, as follows:

$$P = \frac{\Delta_y}{d} * 100 \tag{2.6}$$

2.5.7 Procedure Defined by Standards

The length of each test piece is to be measured using the Standard D2212 Test Method for Determining Dimensions of Thermoplastic Pipe and Fittings [32].

- To determine the length of each specimen to the nearest 1mm or better by making and averaging at least four equally spaced measurements around the perimeter.
- To determine wall thickness make at least eight measurements equally spaced around one end and calculate the average wall thickness.
- Determine the average outside diameter to the nearest 0.2 mm using a circumferential wrap tape or by averaging the maximum and minimum outside diameters as measured with a micrometre or calliper.
- For OD(outer diameter)-controlled pipe calculate the average pipe inside diameter (ID) by subtracting two times the average of all wall thicknesses from the average of all outside diameters.

When addressing the positioning of the pipes in the test area before crushing D2412-11 standardises the method.

- Locate the pipe section with its longitudinal axis parallel to the bearing plates and centre it laterally in the testing machine.

- With the deflection indicator in place, bring the upper plate into contact with the specimen with no more load than is necessary to hold it in place. This establishes the beginning point for subsequent deflection measurements.

2.6 Previous and Relevant Testing

It is important to note that the testing being designed and undertaken is a new testing method primarily due to the fact that the testing is destructive. Most testing undertaken in polymer pipes isnt purely to destroy the material but to test the deformation and stiffness under expected environmental forces i.e. underground compression or internal pressure. The testing method designed is to completely crush the pipe with no air gap resulting in the pipe being destroyed, as would be the result of Hiltis fire stop equipment.

The Plastic Pipe and Fittings Association of North America stated that applying crush strength testing to polymer pipes is usually done by placing pipe horizontally between two parallel plate blocks and loading the assembly to crack or break the pipe. However in some situation crack or fracture does not take place therefore the test does not have an end point [8].

Primarily the crush strength test methods are not applicable to thermoplastic pipes due to the high degree of flexibility that these types of material exhibit [8]. The test end point will therefore be defined by the thickness of the pipe at end of the test being equal to twice the wall thickness of the pipe initially. This would mean that no air flow would be possible through the pipe.

Although testing of this kind has not been undertaken there are some similar compressive tests that have been done on polymer types and these can act as somewhat of a precursor to what we can expect from the results. The compression test undertaken by Avallee, Belingardi and Ibba on multicellular polymers such as polyurethane and polypropylene cubes produced results shown in Figure 2.9 in the form of a stress strain curve.

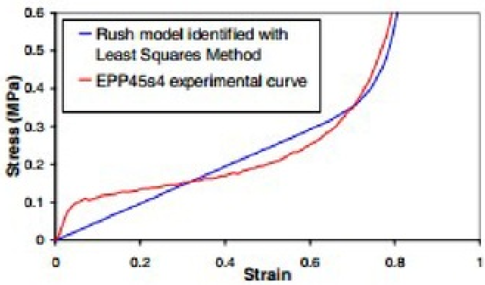


Figure 2.9: Similar Compression Test Profile [7]

Although this test acts as a good representation of what we can expect from the compression of polymers, the geometry of the test pieces are very different to what is to be tested in this report, along with the test having a higher compression rate (60mm/min) and the multi cellular structure of the pieces are far from similar to the pipes that are being tested [8].

The benefits of foam or cellular compression testing is they should have a similar stress strain curve as there is the tendency for the material to take a high load then slight internal compression takes place before a gradual increase in load. The labels of various stages are shown in Figure 2.10

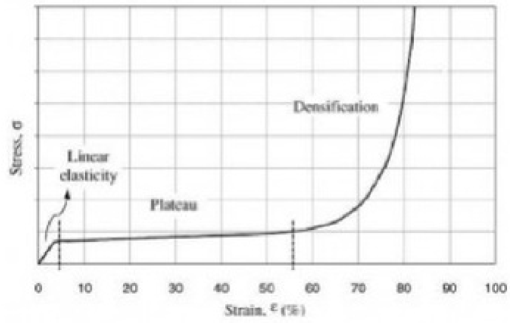


Figure 2.10: Polymer Compression Test Characteristics [7]

The testing undertaken produced similar data to that produced in the previous literature being also on varying densities of polyurethane. The literature produced by G. Vladimir shows repeated trends for compression plots, but once again the geometry of tests pieces and the compression rate differ significantly from a proposed test method [35].

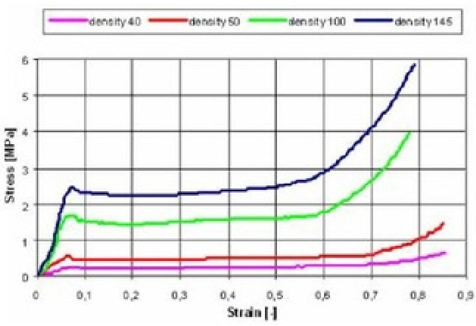


Figure 2.11: Polymer Compression Test Results [8]

The current form of testing undertaken by various firestop companies to replicate these situations tend to be very expensive and have a significant negative environmental effect.

The testing that will be undertaken in this project hopes to minimise these negative effects while giving viable testing results on the crushing of polymer piping by firestop products.

Chapter 3

Heat Testing Apparatus Design

3.1 Design Considerations

The testing apparatus that is to be design and built must meet a variety of requirements to ensure a correct and viable test. The testing this design must allow for is heating of the polymer test piece then instantaneous diametral crush. In doing so the apparatus must:

- Ensure no damage is done to test equipment
- Not impede the testing of the material
- Allow for appropriate heating of pipe test pieces

To ensure that the heating of the test piece happens correctly the apparatus must be able to ramp up heat quickly to intumescent activation temperature (180C), then be crushed through the diameter of the pipe, mimicking what would be experienced by a pipe from a fire stop collar in fire conditions. The quick ramp up of temperature through a heating plate is vital as this is a distinctly important characteristic of building fires.

The characteristic of building fires in fire proof rooms, also known as compartment fires, have a very unique temperature profile, that being the temperature increases very rapidly. This can be seen in the paper Study of the fire characteristics of multi-source fires in the confined corridor where a fire was set in a confined spaced being a corridor and the temperature increase was measured as the fire volume increased over time.

The figure 3.1 below shows the temperature development in a fire over a period of 450s. The important and relevant information from this data plot to be taken for this report is that the temperature of 180°C is reached at approximately the 3.5 minute mark. This fast rate of temperature increase was a major design consideration as it was intended to be mimicked via the testing apparatus it in the test procedure. It is important to note that these values were taken from a multi-source fire test so may not strictly represent the exact fire development. However, to address this the value plotted is from a thermocouple situated close to a single fire and the most suited position to minimise the effects of the secondary fire [9].

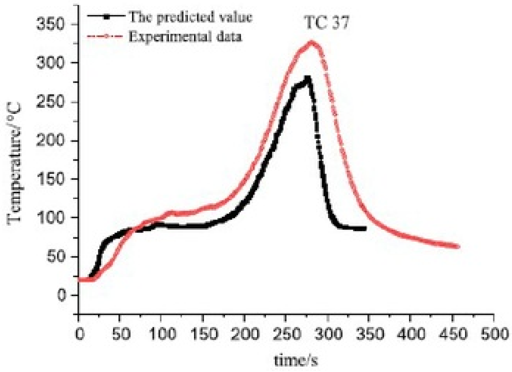


Figure 3.1: Temperature Increase in Compartment Fires [9]

Another major design consideration is to understand that this apparatus is to be built around the Instron Universal Tester and ensuring that the rig will not impede or alter the testing in any means. Any interruption to the Universal Tester would make the data produced void as well as making any comparison of it with room temperature testing impossible. It is equally as important to ensure no damage is done to the Instron due to value of the machine and as any repair to damage is likely to be very expensive. As well damage to the machine may not occur physically or aesthetically but, instead, affect the results produced by affecting the internal workings such as load sensors.

To produce correct and useable data it is important that during the test that the apparatus isnt going to effect the results. This can be addressed by ensuring the materials in the test apparatus are stronger than the max force that will be experienced by the pipe allowing for force and extension to of the pipe to not be effected. Progressive testing was undertaken to ensure that the pieces added to the machine via the rig, would not affect measurements in this manner.

3.2 Heat Resistant Tile

In a measure to protect the Universal Tester and the compression platens from the heat to be produced, a fire brick is positioned between the heating plate and the compression platens. This ensures that no heat will transfer through to the platens preventing damage such as warping and heat expansion.

Ideally a refractory firebrick would have been used however, sourcing one that met the thickness requirements within the budget and time frame was very improbable. Instead a porcelain tile was used to separate the heat source on both the top and bottom platens, as the same refractory property (resistance to heat) can be achieved due to the tiles material make up.

The porcelain tile was chosen due to the ideal thermal properties of the tile material and the fact that it is easily procurable. The manufacturing process of tiles involves the mixture of raw materials such as clay, chemicals and other additives, the forming of a shape through pressing and moulding, followed by the firing process [36]. The materials used in this manufacturing process gives the tiles a very low thermal conductivity and refractory properties, meaning that the heat transfer though the material is very low such that direct contact to high temperature on one surface will, for a reasonable period of time, result in the other surface of the tile remaining cool [37].

The application of this property for the test needs meant that even a thin tile would be effective in protecting the compression platens from the heating plate due to the short heating process that is taking place. The manufacturing also involves the firing process where the bound and moulded materials are heated to extreme temperatures, drying the materials out and giving the ceramic it a high tensile strength making it effective to use in compression testing without effecting the results.

3.3 Heating Plate

To replicate the temperature increase that is experienced by a polymer pipe in fire conditions a metal plate was implemented to transfer heat to the pipe via conduction. This was done via two contact points, above and below the pipe, supported by the compression platens. Although this method of heating the pipe is not ideal, it allows a reasonable replication of fire temperature conditions whilst still being within the time and cost limitations of the project.

When it came to picking the plate material the most important material property to consider was thermal conductivity. A high thermal conductivity allows for the quick increase in temperature of the plate and ultimately the pipe being heated. The material must also have a relatively low thermal expansion coefficient, be readily available and easy to cut and shape as required.

The material chosen to be used for the heating plate was aluminium primarily due to the ease of access and the relative cheapness of the product. With a thermal conductivity of 244W/mK for a temperature range of 0-100C, aluminium has a high enough value to allow for the quick heating of the pipe while still being strong enough, at those temperatures, to allow for the compression testing of the polymer pipe. In designing the securing bracket for connecting the plate to the tile and platen, the thermal expansion of the aluminium needed to be considered.

Two aluminium plates were cut at 100mm*50mm*10mm.

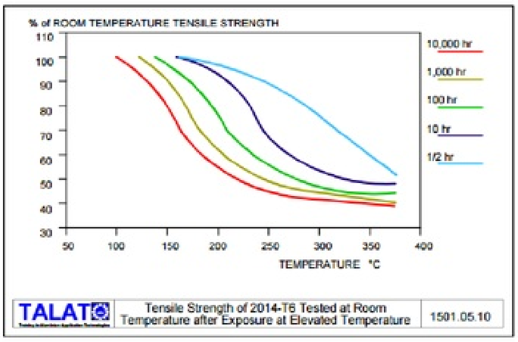


Figure 3.2: Strength of Aluminium at Various Temperatures [10]

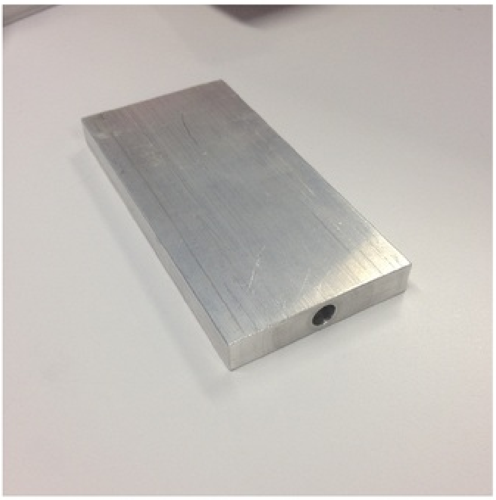


Figure 3.3: Aluminium Plate Constructed at METS [11]

3.4 Cartrige Heaters

As mentioned previously, the heating up of the plate has to replicate, to the best abilities, that of a compartment building fire and its temperature increase. To best replicate this it was decided that high density heater cartridges would be used.

Cartridge heaters consist of a resistance wire (Nickel Chromium) wrapped around a magnesium oxide core with pair of refractory Nickel rods contacting the resistance wire at both ends. This is then inserted into a stainless steel tube with the remaining space filled with magnesium oxide (MgO). When connected to a power source the resistance wire within the cartridge gives off heat which transfers the heat to the MgO, and the stainless steel shell in turn. To install the cartridge it is a simple as drilling an installation hole in the aluminium plate and inserting the cartridge within the plate. Providing the cartridge is installed correctly the heat will be conducted to the material it is fitted in causing an overall increase in temperature [38].

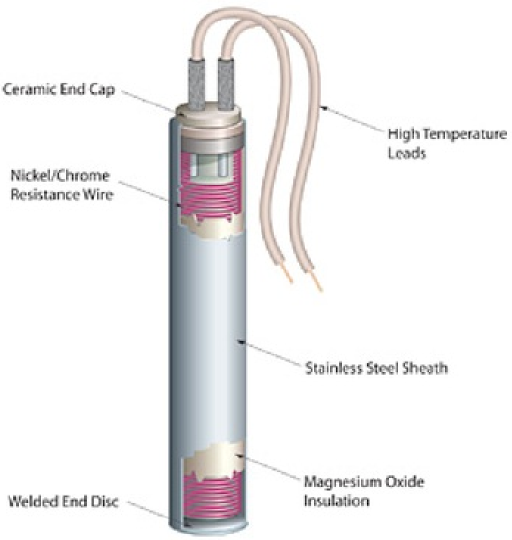


Figure 3.4: Heater Cartridge Internals [11]

The cartridge heater chosen was a Hotco 250W, 63.5mm long and 6.35mm diameter with one being installed in each of the heat plates via a suitable hole being milled into each of the aluminium heating plates.

3.5 Thermocouples

Once the total heating apparatus was installed with the heaters active in raising the temperature of the plate, some control and means of measuring the temperature must be

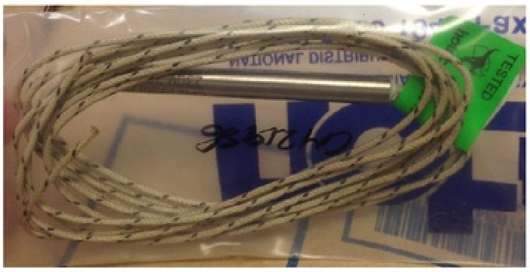


Figure 3.5: Purchased Hotco Cartridge Heater

had to show the instantaneous temperature of the heating plate. The thermocouple below was inserted within the aluminium plate to give feedback on the current temperature of the plate via a Digital Multimeter (DMM).

Thermocouples work under a principle whereby if two dissimilar metals are joined at each of their two ends and are experiencing different temperatures, a potential difference (voltage) develops between the two. This characteristic is called the Seebeck effect and works on the basis that just as at high temperatures molecules move faster, electrons are more likely to produce a current between the two materials. Depending on the metals in the thermocouple, the magnitude of the voltage produced reflects a temperature value to be read.

The thermocouple used in the heating plate is a J-type thermocouple meaning that the two metals the thermocouple contains are iron and a copper-nickel alloy called constantan [39]. This particular thermocouple was selected as it has a restricted temperature range (0 to 750C) but as a result has a higher level of sensitivity. This Hotco thermocouple is 28.575mm (1.125inch) long with a diameter of 4.7625mm (3/16 inch).

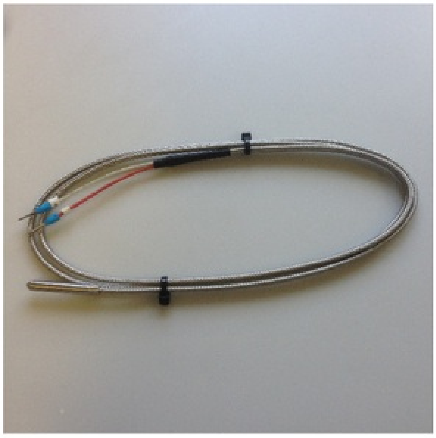


Figure 3.6: Purchased Hotco Thermocouple

3.6 Final Rig

The final apparatus constructed through Macquarie Engineering and Technical Services (METS) is shown below in Fig 3.6. As can be seen, the aluminium heating plate is beneath the refractory tile attached via an aluminium bracket with 2 upper and 1 lower 8mm threaded bolts connecting both the aluminium plate and the Instron compression platen. On the lower bolt a white polytetrafluoroethene (PTFE) bush can be seen which has two functions. Firstly it minimises the direct transfer of heat through the plate to the bracket and secondly being a polymer allows for some flex through the rig, ensuring that the plate is taking the compression load and not the bracket.

Figure 3.7: Completed Rig

The figure beneath shows that fully wired aluminium heat plate with tile while not attached to the upper platen. The initial cartridge heater wires were wrapped with a higher insulation polymer cable to ensure that connecting to the high current mains would be done safely as well as the standard male power plug connected. Another hole was added to each of the aluminium plates to allow for an earth wire to be installed as to meet the saftey requirements set out by Macquarie University. The white tag attached to the power cable is the eletrician's approval once again via METS.

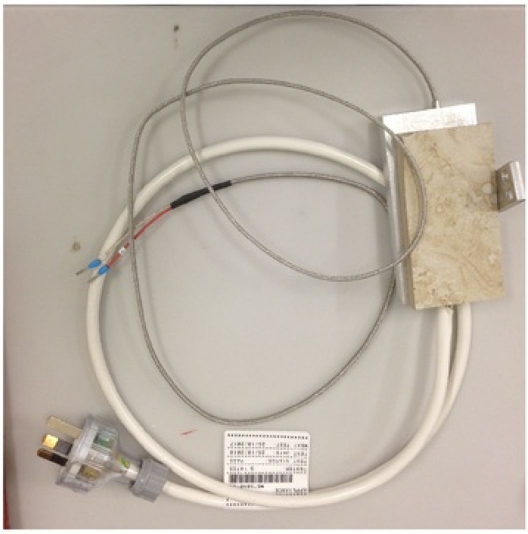


Figure 3.8: Power Supply Design for Heater

Chapter 4

Testing Procedure

4.1 Material Preperation

Each of the four pipe types were all subject to the same material preparation although there was some variation in pipe diameters (θ) sourced. It was decided that a variety of lengths would be chosen to undergo the compression plate tests. The test dimensions were as follows:

As required from ASTM D-2412 testing standards, before every test each pieces length was measured using a calliper by making at least four measurements equally spaced about the piece and averaging. As well each pieces diameter was measured at least 8 times using a calliper and averaged [31,32].

As required from ASTM D-2412 testing standard the temperature for testing was 23 $\pm$ 2°C and the test material was exposed to this temperature for 4 hours in air prior to testing [31].

As required from ASTM D-2412 a minimum of three tests must be done on each different length of piece. As a result the following number of pieces were prepared for testing and were done so ensuring the ends of specimens were cut square and free of burrs and jagged edges as per the aforementioned standards [31].

For HDPE, PEX and PEX AL PEX:

For PVC only:

The material preparation was done via METS where the materials were placed in a

Material	Length =0.5*θ (mm)	Length =θ (mm)	Length =2*θ (mm)
PEX	12.5	25	50
HDPE	12.5	25	50
PEX AL PEX	12.5	25	50
PVC	10	20	40

Table 4.1: Test Piece Dimensions

Length (mm)	Number of Pieces
12.5	4
25	10 or more
50	4

Table 4.2: Material Preperation Instructions 1.

Length (mm)	Number of Pieces
10	4
20	10 or more
40	4

Table 4.3: Material Preperation Instructions 2.

lathe and cut length measured digitally within the equipment. This process minimised the production of burs and ensure a square cut on each of the test pieces.

4.2 Room Temperature Test Procedure

4.2.1 Universal Tester Setup

The Instron Universal Tester was initially set up as shown in the image below, that is, with an upper compression platen of a diameter of 50mm and the lower compression platen of 150mm attached.

Once the tester was set up and all the necessary pins and couplings attached, the tester was then calibrated through the Blue Hill software (Instron Testing Software) for a compression test. This involved selecting the compression test function, inputting a compression rate (mm/min) and an initial positioning of the anvils i.e. a designated initial separation. This initial position can be controlled via the machine mounted control shown below. This control allows for jog(fast) and fine positioning of the upper platen, starting and stopping of the tests, live measurements of extension and load along with the ability to reset the extension to zero (reset GL) and finally allow for the return of the upper platen to the initial gauge length. The variuos stages of setup can be viewed in the Appendicies.

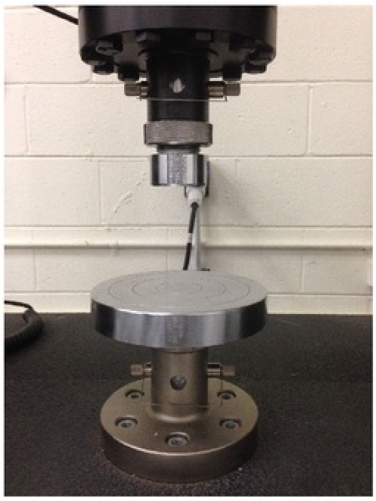


Figure 4.1: Instron Tester Initial Set Up

Figure 4.2: Instron Machine Mounted Control

4.2.2 Preliminary Safety Test

Once setup as above, a preliminary test was undertaken to ensure the procedure was safe. A low compression rate was input of 0.5mm/min. This was done initially to ensure that the safest test method could be implemented as this was one of the first tests of its kind. During the test the specific areas that were scrutinised are as follows:

- Shrapnel production
- Possible sources of injury e.g. pinching of limbs
- Safety as a whole throughout the test
- A repeatable test which produced high quality results

A PEX test piece of 25mm length and diameter was placed in between the platens as centrally as possible underneath the top anvil and the top anvil dropped till touching but exhibiting 0N±0.5 of force. This can be controlled on the Instron monitor mounted on the side of the machine and was done very carefully in this test to prevent pinch or crushing of limbs.

Once the piece was in place, an exclusion zone was enforced and set out on the ground using tape, along with safety glasses being worn by all within the testing room. The test was then started, followed through until it appeared from viewing that a complete crush had occurred and manually stopped. Only once the test had ended and the force removed off the polymer could anyone enter the exclusion zone. It was then established from this test that fracture and production of shrapnel would be highly unlikely.

4.2.3 Initial Test Procedure

The initial test method was undertaken without any set end point but still met the requirements set out by the ASTM D2412 standards for a compression test [31]. That being a set compression rate of 12.5 mm/min ±0.5 and pieces dimensions measure in accordance to ASTM D2122 [32]. However, the test was deemed finished through visual means. That is, without entering the exclusion zone, the test was viewed from a position level with the lower wall of the test piece and once the test piece appeared to be completely crush i.e. internal diameter was equal to zero, the test was manually stopped. The return button was then pressed and the piece removed.

This test procedure was undertaken on 12 samples, 3 of each material type with all dimensions of length equal to diameter.

4.2.4 Refined Room Temperature Testing Procedure

Before each test the dimensions of each test piece were measured to the standards set out via ASTM D2122 [31]. This allowed for and end point to be set for each piece individually ensuring that a complete crush occurred for every piece with the end point being taken as the average of all the internal diameter values taken. This allowed for a highest chance of full crush to take place for every test piece. For safety another end point was defined for each piece and that was a max force to prevent sharp spiking of force as this would be greatly increase the chance of shrapnel.

Once calibrated for a compression test the compression rate was reset as 12.5mm/min as defined by ASTM D-2412 [31]. The Universal Testers measured load was then balanced, ensuring that no load was being experienced by the platens and they werent in contact with each other. A test piece was then centrally placed on the lower platen between the two platens and the upper platen dropped until touching with 0N±0.5 of force on the piece. It was ensured at no point would any test piece sit outside the bounds of the upper platens 50mm crushing face. Before the testing was started the gauge length was reset to zero to ensure extension was measured from the initial starting point and the test was then commenced.

Once the test was started it was left to continue till it met any one of the set end requirements whether that be force or upper platen extension. Once the test was complete the raw data was saved and using the return button, the top platen was replaced to its start position and the test piece removed.

This was the test method repeated for three of each materials where length was equal to diameter as well as 3 of each material where length was equal to half diameter and length was equal to double the diameter. That is, a total of 36 tests done where results were recorded for analysis.

4.3 Rig Design Testing

The rig design testing followed the same procedure as the Refined Room Temperature Test Procedure however, no force limits were set as to not diminish any effects that may have been produced from modifications. The only change was the addition of various materials/apparatuses in the set up to ensure that the introduction of these pieces would not affect the data output by allowing comparisons to be made between normal tests.

4.3.1 Single Tile Test

In this test there was the introduction of a single refractory tile to the bottom 150mm platen. As this is a stationary platen the tile was not secured, however was placed carefully in the centre of the bottom platen. The test piece was then placed carefully on the tile with the upper platen lowered much the same as before, ensuring that the test piece was as centred within the face of the platen as possible. Once secured in position by a force of 0N±0.5 the test was started. The end point was defined as when extension was equal to the averaged internal diameter of the pipe which in this test was a 25mm PEX piece.

4.3.2 Upper and Lower Tile Test

This test once again followed the same procedure defined in the refined test procedure but with a changed set up. In addition to the single bottom tile in the previous test set up another smaller tile was added to the upper platen secured via the force of the Universal Testers upper platen pushing the tile down onto the test piece once again being 25mm PEX. Once the force exhibited on the test piece was 0N±0.5 the test was started and completed once the extension was equal to the averaged internal dimeter of the pipe.

4.3.3 Full Rig Test

The full rig test involved the introduction of the high temperature test rig shown earlier in the Fig The rig, containing the secured aluminium heating plate and tile, was installed to the upper platen ensuring that it sat level. There was also the introduction of the lower aluminium heating plate to the bottom tile sitting as centralised under the upper platen as possible. The rig at this testing stage was not connected in any means to mains power as this test was undertaken at room temperature throughout.

The rig was then calibrated to account for the extra mass added to the upper platens. A 25mm PEX piece was then placed atop the lower heating plate and the upper platen lowered until the piece was touching and exhibiting 0N±0.5 of force. The test was then started and finished once again when the extension of the platen was equal to the pipes internal diameter.

4.4 High Temperature Testing

The following test procedure aims to produce a quantitative analysis of the effects that high temperatures have on the strength of polymer pipes while being exposed to a diametral compression.

4.4.1 Safety Considerations

This procedure requires diligence in regards to safety. There are three main areas that must be given the upmost consideration. These are:

- High temperature materials
- High voltage electricity
- Crushing of body parts

As mentioned in the room temperature testing, when undertaking a compression test, crushing of body parts has the possibility of being a source of injury and great care must be taken to avoid this. In addition to this, the following procedure involves the introduction of heating plates meaning that there is going to be multiple pieces of high temperature during and after the test. It is a necessity to have heat resistant gloves when handling any pieces that have been in direct contact with the heating plate. As well as this polymers when heated up tend to melt and with this comes the chance of the plastic sticking to skin and causing burns.

The cartridge heaters within the heating plates require mains power to operate as mentioned previously. The heating plates were assembled, wired and certified through METS to ensure that no electric shock or electrocution would occur when current was supplied to the plates.

4.4.2 Test Setup

The method for this test involved the installation of a tile and an aluminium heater plate placed on the lower platen and the high temperature testing rig to be installed on the upper platen using two 8mm screws to tightly secure the rig in place. Once this was installed both the heat plates were attached into mains power (240V, 10A) but not switched on. Each J-type thermocouple was then attached to their respective Digital Multimeters (DMM) with the switch turned to AC mV and then the thermocouple was placed securely in the installation holes within each of the plates. It was ensured that both DMMs were reading the values representative of the room temperature before each of the tests.

Before any action was taken the Instron Universal Tester was calibrated to take into consideration the extra weight that had been added to the upper platen. A compression test was then set up with a compression rate of 12.5mm/min ± 0.5

4.4.3 High Temperature Testing Procedure

Once set up was completed a test piece was positioned between the two metal heating plates, centralised under the platens position above the aluminium plate and tile. The upper platen was lowered till the heating plate had contact on the test piece with a force of 0N$\pm$0.5. The heating stage of the testing was started when the power supply was switched on and therefore the cartridge heaters started to warm up the heating plates. With both the cartridge heaters being under the same power supply conditions, the heaters warmed up at the same rate, both being monitored by the thermocouple readouts on the DMMs. Once the plates reached 180°C the power supplies were switched off and a quick heat measurement was made with the infrared thermometer of the internal walls. One of the internal area of where the top plate had contact and one on the internal side of no contact. The test was then started and completed once the extension of the upper plate was equal to the average initial internal dimeter of the test piece. The upper platen was then returned its initial position. This testing method was used to high temperature test three length equal to diameter polymer pipes of each material being a total of 12 tests.

Chapter 5

Results

The following section displays the imperical data produced from room temperature and high temperature testing as per the various aforementioned procedures.

5.1 Initial Testing

5.1.1 Safety Test

The data plotted below is the raw data produced from the safety test. This test was done with a 25mm length of PEX pipe

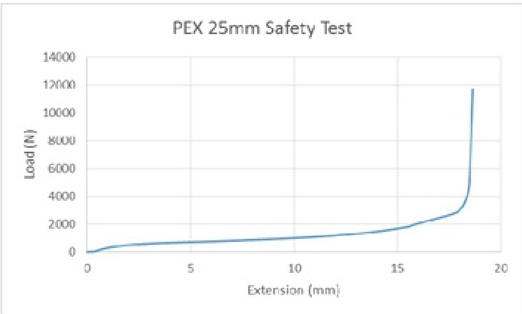


Figure 5.1: Safety Test

5.1.2 Initial Procedure Results

The four data plots below are that of the 12 initial testing method tests whereby an end point was not necessarily defined. The data produced was done so with an aim to develop the test procedure for the following tests. As well the tests allowed for refinement of the data plot method. The following figures display the first three test on each polymer pipe type. Each graph displays all three tests raw data on the one plot. The results shown in figure 5.2 it is clear that in test 1 the force spiked quite quickly as opposed to the other two tests which ended at around the 6000 N load, having followed the same trend up to that point.

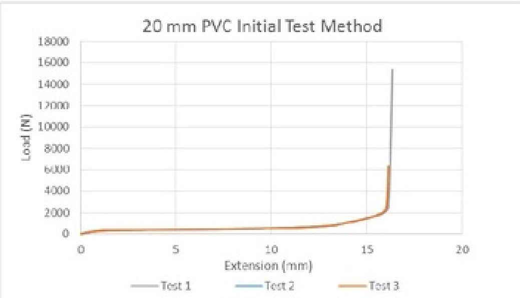


Figure 5.2: Initial PVC Compression Test

In figure can once again a spike can be seen in test 1 with it reaching close 18 kN before the test ends. Tests two and three ended quite a bit earlier at approximately 7 kN and 6 kN respectively with test two carrying a higher force from the 17 mm to 19.5mm point, just before the rapid increase in force

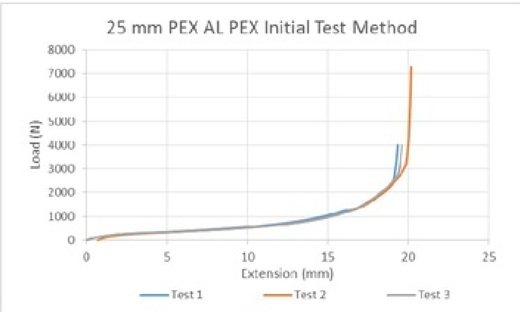


Figure 5.3: Initial PEX AL PEX Compression Test

In figure a very consistent path can be seen through all three of the PEX tests with no real deviation between any of the tests. This is a sign of a solid test method throughout as it displays consistency.

The data plotted in figure is once again displays consistency throughout the entirety of the compression test. Although there is a slight variation between the end points as a result of no real defined end points between tests.

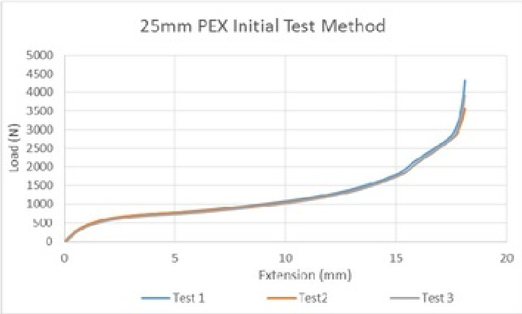


Figure 5.4: PEX Initial Compression Test

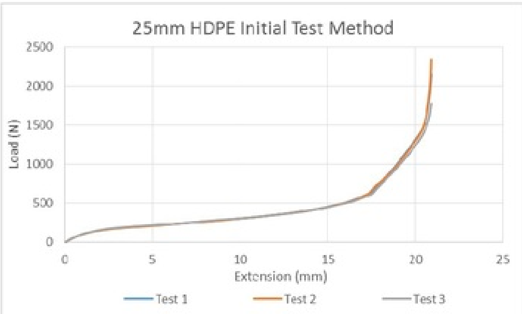


Figure 5.5: HDPE Initial Compression Test

5.2 Refined Procedure Results

The following four plots are the product of a more refined testing method. Most of the plotted raw data had one, if not more, defined end points to the testing.

5.2.1 Initial Refined Testing

The data displayed in Fig 5.6 can be identified as part of the refined test method. This should be noted by the almost identical end points at 3 kN and approximately 16mm extension.

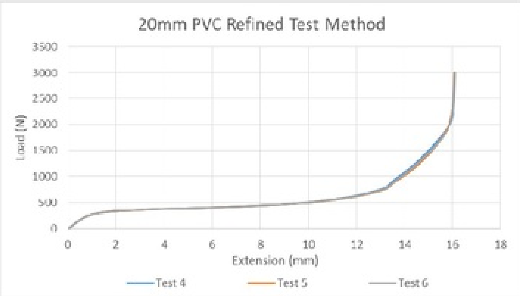


Figure 5.6: PVC Refined Compression Test

The 25 mm PEX AL PEX raw data plot seen in Fig5.7 shows some variation in end points

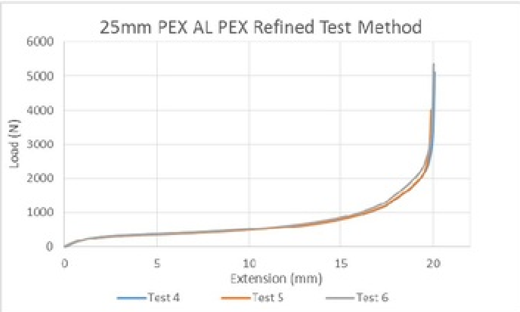


Figure 5.7: PEX AL PEX Refined Compression Test

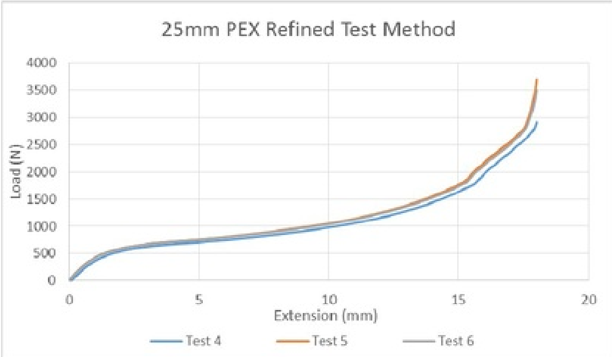


Figure 5.8: PEX Refined Compression Test

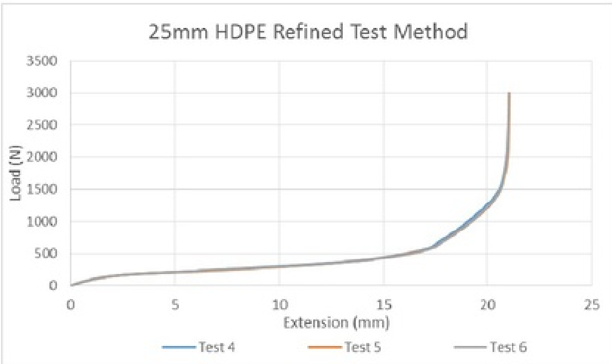


Figure 5.9: PEX Refined Compression Test

5.2.2 Length Comparison

The graphs seen below are a representation of the raw data of a variety of different length pieces of each polymer pipes type. Each of the half and double lengths are the representations of averages made from the raw data. This allows for a clear representation of the different load progressions throughout the tests. Slight kinks in the lines can be attributed to slight averaging anomalies and necessarily from significant testing events.

As can be seen in all of the figures below, the larger the length of test material, the more amount of load is required to entirely crush the piece. The addition of the standard, length equal to diameter gives a point of reference and comparison for each of the changed length pieces.

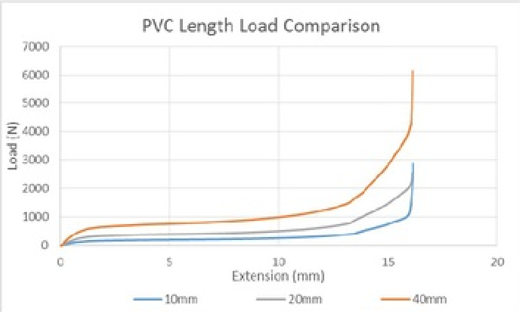


Figure 5.10: PVC Length Comparsion

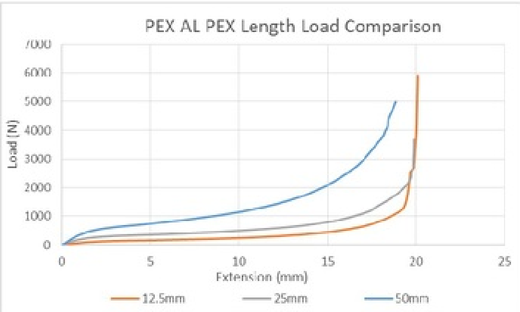


Figure 5.11: PEX AL PEX Length Comparsion

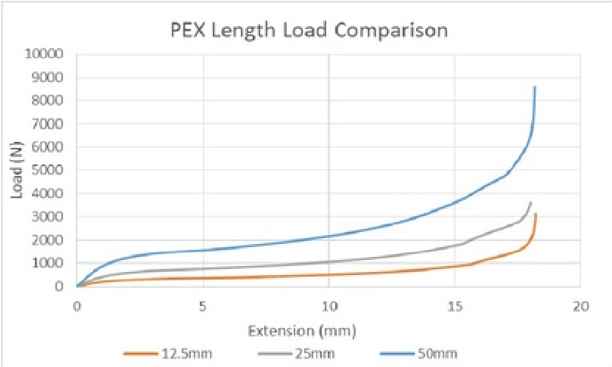


Figure 5.12: PEX Length Comparsion

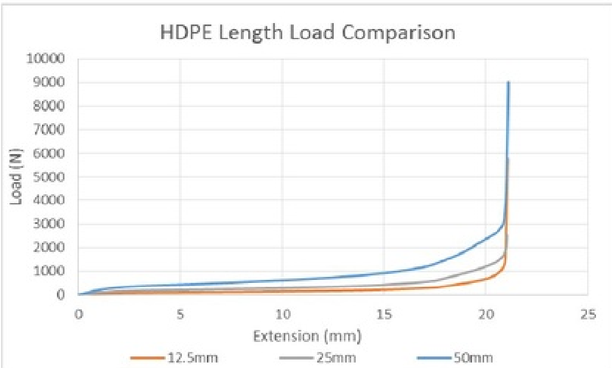


Figure 5.13: HDPE Length Comparsion

5.2.3 Material Comparison

The comparison chart below shows four lines in the figure below represent an average of all the refined test method data for each material type. That is each line represents the mean of 3 tests. A clearly recognisable trend is the minimal amount of force required to crush the smaller PVC pipe and that on average the PEX pipe took the most amount of force to crush completely. Although there is a large variation between the load and extensions of each pipe type, all of the pipes appear to follow a similar path if scale is disregarded.

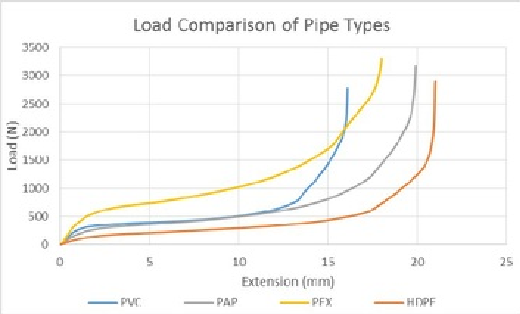


Figure 5.14: 25mm Pipe Material Comparison

5.3 Design Testing

The data in figure are, all but one, representation of singular tests. All of which are under very different test circumstances, and even so, are still very similar. The PEX Average line is added to be able to make comparisons between a standard test and the addition of different variables in the three other tests.

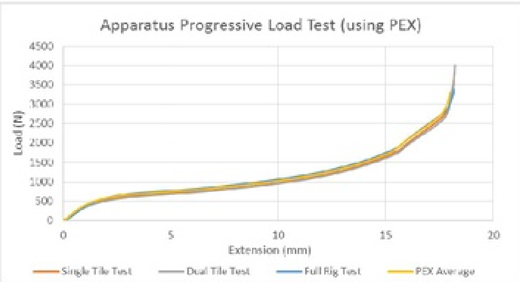


Figure 5.15: Test Piece Design Comparison

5.4 High Temperature Testing

The following four graphs are produced from undertaking the high temperature testing procedure. Each graph shows 3 different test undertaken on the same material type with the length equal to diameter dimensions. The plot shown in figure

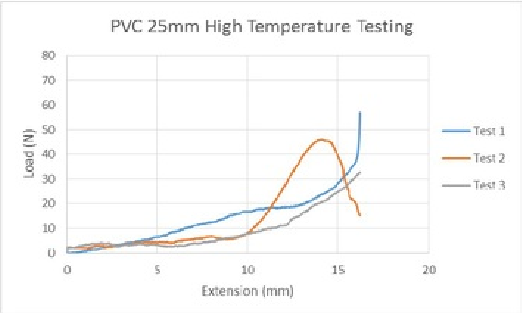


Figure 5.16: PVC High Temperature Testing

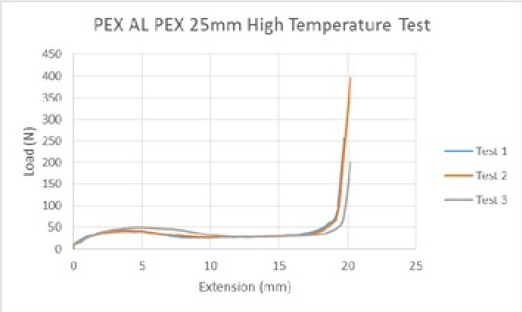


Figure 5.17: PEX AL PEX High Temperature Testing

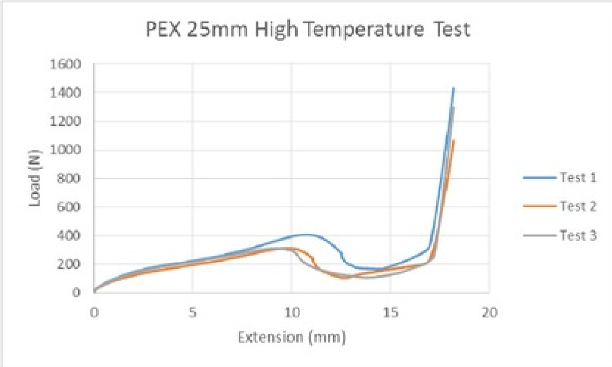


Figure 5.18: PEX High Temperature Testing

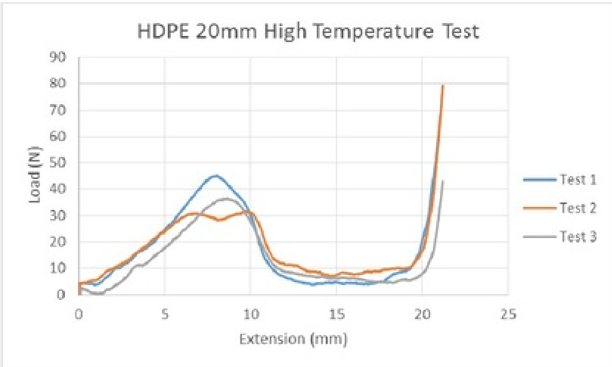


Figure 5.19: HDPE High Temperature Testing

Chapter 6

Discussion

The following section investigates, analyses and scrutinises the results produced from the procedures developed through this report.

6.1 Initial Testing

The purpose of this project was to develop a testing method for the diametral compression of a wide variety of polymer pipes at varying lengths that allowed for consistent and repeatable results. The initial testing design allowed for analysing safety of the tests as well as developing the test design to a more consistent and controlled procedure by being able to define an end point.

The process explained in the initial test procedure was an untested process primarily based off of the requirements of ASTM standards [31]. It had been mentioned that in previous testing methods, defining an end point of a crush test was challenging and had to be adapted to the situation to ensure that the data produced met requirements [7]. An example of an uncontrolled test can be seen in the initial PEX AL PEX and PVC tests where the forced spiked very quickly once the piece was squash flat also bringing safety of the test into question.

As a result of the test mentioned above, the flat squash of the polymer pipe was then defined as double the initial wall thickness and this was introduced as an end point to the test method in the Blue Hill software. However, this lead to the tests, in some cases, ending early, and in other cases, the test still extended on to a large compression force. To address the force spike, a max load end point was added to the test method in the Blue Hill software. The pairing of the two end points in the refined test method allowed for a more controlled and repeatable method, and therefore the production of more consistent data.

Although the initial test method did require some refinement, the data procured still allowed for some analysis of the pipe properties. Characteristics such as elastic and plastic regions of the compression are identifiable as well as a consistency among results produced and similarity to some related testing [8, 35]. This ultimately legitimises the approach of the initial test method.

The purpose of the initial test method was to establish foundations for a test method that had had never been done before. Considering this, the results produced from these tests helped drive the progression in testing as well as defining safety requirements for the refined test method future tests.

6.2 Refined Testing Method

The refined test method developed on the results produced in the initial test method, primarily the introduction of defined end points for each test. When looking at the load vs compression plots there are a couple consistent trends throughout all of the tests. As stated in the previous section, consistency between the plots is a good sign of a well-designed test method, especially when spread amongst a variety of material types and test piece dimensions. Along with this, consistent plot characteristics can be linked to reliable data and are prevalent throughout the refined test method.

The first plot characteristic occurs at the start of the test and is a result of the standard force ramp up as the Instron tries to keep to the set compression rate. This is accompanied by the elastic deformation of the pipe where by the pipe bends under the force of the plate pushing downwards on top. At this point if the force was then removed the pipe would flex back to its original shape without any permanent shape change. During the test this was view as the originally circular pipe being ovular and then with the piece of the pipe that was initially touching the plate pulling away from the plate caused by the tension of the outer surface of the pipe.

Following this, the plastic deformation takes place in the pipe. This is defined by the pipe undergoing a permanent shape change whereby when the force is removed from the pipe, to some extent, the pipe will hold the shape that it is being forced into. This is a result of some bonds in the molecular structure being broken to the extent of no recovery. This happens consistently throughout all the tests and is a result of the pipe compressing to the point where the two opposing walls touch.

Due to the presence of the second contact point the force of the lowering plate is going to be spread out more evenly through the piece therefore increasing the overall stiffness of the pipe. This is an important characteristic of how polymer pipes deal with compression force. This contact point, as expected, is accompanied on the plots by an increase in force required to compress the pipe. This characteristic can be seen in all room temperature tests to some extent and can be visually identified an increase in gradient of the line. This increase in gradient continues as the pipes comes closer to the being crushed completely flat signifying the end of the test.

This particular attribute only come about due to the type of compression test being used. Once the force was removed from the pipe the pieces tended to flex back towards their original shape however only partially. This can be explained by the way the test was carried out and how the compression affected the pipes. When the pipe were squashed the force was primarily felt on the faces not touching the platens as it forced them to bend. This bend being the outer surface experienced an extension force and the inner

Figure 6.1: PEX Wall Contact Point

wall, a compression force. The rest of the test piece does not experience too much stress and therefore does not experience plastic deformation causing the pieces to regain their shape.

Although majority of the resistance force to the compression can be attributed to the stiffness of the pipe, it is important to note that some of the force is likely to be sourced from the elongation of the pipe perpendicular to the force of the plates as it spreads via compression. The pieces post testing can be viewed in the appendicies.

When analysing the plots individually, it can be seen in both the HDPE and PVC the presence of a symmetrical relationship between all the tests. Looking at the PEX AL PEX plot it appears that the load dependent end point was not set low enough although no large peak occurred due to the extension endpoint. There still seem s to be some discrepancies in the end point for these test. This may be sourced from experimental error or discrepancies in the measuring and averaging of the internal diameter. The overlap of the butt welded aluminium within the layered PEX did cause a slightly larger thickness and may have causes some discrepancies in determining internal diameter.

There is also a slight inconsistency in the PEX plot of raw data. It can be seen that after approximately the 5mm extension point the Test 4 load rate starts to differ to the rest of the tests as well. The data still carries the same characteristics, specifically the force at which the wall touch occurs. The source of this error could be numerous things such as material fault, improper test procedure or equipment error however as the characteristics occur at the same loads the results are just offset by the extension point leading to material fault being the most probable cause.

6.2.1 Related Testing Comparison

Overall the results of the refined testing procedure help to support the quality of the refined testing method, especially when comparing to expected results. When looking at other examples of polymer compression testing mentioned in the background section, we do see a distinct similarity. The result certainly follow the model put forward of elasticity, plateauing and densification however not as strictly, most likely due to the varying geometry of the test pieces [8,35].

When comparing the two the main difference is the firm presence of an elastic limit in the model compared to these results where the elasticity fades into plastic deformation. This can be explained with the difference in geometry where in the foam modelling there is a multicellular make up in the material as opposed to pipes where the void between material surfaces is quite large in comparison.

The similarities between the related testing is also quite prominent. There is a definite plateauing effect of load progression in all of the tests where the load increase happens at a lesser rate. Densification happens in some form as the internal diameter decreases with an example of this being the touching of opposing walls resulting in the increase in gradient of the load to extension.

6.2.2 Length Comparison

The length comparison involved the testing of polymer pieces with a length of half and double the pipe diameters. This was done firstly as a measure of the test methods effectiveness as well as a means to finding out how length of a piece affected its strength.

As expected throughout all the results there was a distinct pattern of the smaller length pieces being more susceptible to the force and the longer test pieces requiring more load to crush. This can be explained by how the force is spread through the material through compression. With more surface area experiencing the same force then it is expected to more load will be require to crush. When analysing the data it was noted that each line was, on average, double the force of the half-length of that piece.

The occurrence of a relationship between load required to crush the piece and the length of the piece being consistent through the testing is puts the procedure in a positive light. The fact that is also and expected result is equally as positive.

Overall the results produced were solid however there are some errors that would be more refined by repeating the tests for a wider variety of test lengths. This would most likely allow for a more consistent relationship to be developed.

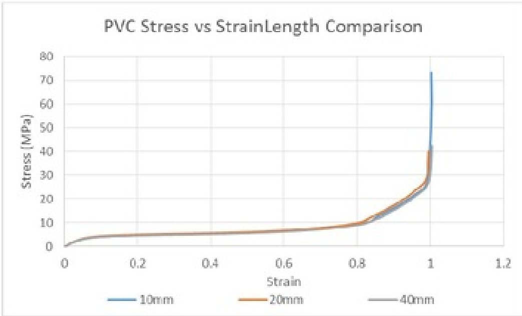


Figure 6.2: PVC Length Comparison: Stress vs Strain

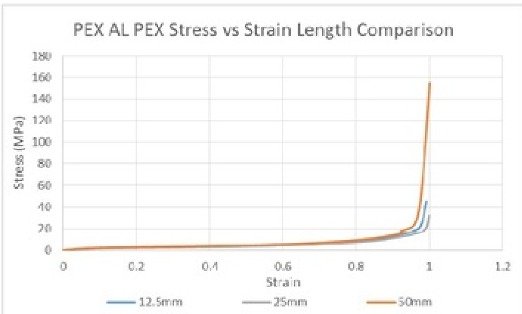


Figure 6.3: PEX AL PEX: Length Comparison: Stress vs Strain

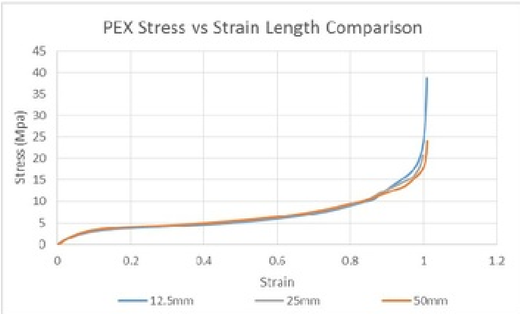


Figure 6.4: PEX: Length Comparison: Stress vs Strain

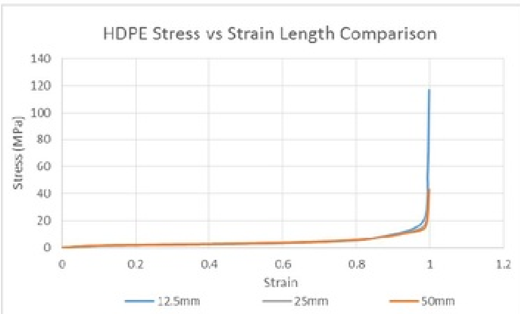


Figure 6.5: HDPE: Length Comparison: Stress vs Strain

6.2.3 Material Comparison

Because of the varying dimensions of each of the pipes, this is the point where the production of stress strain graphs can be helpful for comparison. When viewing the plotted averages from the results section it gives little to no comparative information. PVC seems to be able to less force but its also a shorter length and thinner walled than most of the other pipes.

When this data is plotted into a stress vs strain diagram a different interpretation can be made. It appears that PVC, as expected based on material properties has the highest stress of all the other pipe types. Also, as expected the HDPE pipe requires the least amount of stress to crush.

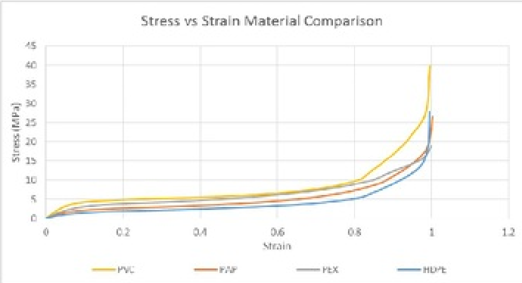


Figure 6.6: Material Comparison: Stress vs Strain

Engineering Stress	Contact (MPa)	Final (MPa)
PVC	10.3	39.8
PAP	9.46	26.6
PEX	10.17	20.25
HDPE	5.8	27.83

Table 6.1: Engineering Stress for Polymer Pipe Types

The plotting of these materials in the form of a stress strain curves allows for a more solid analysis of how the makeup of the pipe i.e. layers and materials, changes the amount of force taken. When looking at the PEX vs PEX AL PEX the addition of aluminium clearly ads more strength to the pipe. The fact that there is the same material used but just with a layer of aluminium and that the PEX AL PEX takes more load to crush. The PVC is without a doubt the most resistant to the crush load as expected as this is an understood material property. Once again the HDPE being the weakest material is expected due to the makeup of the material.

6.3 High Temperature

The high temperature testing procedure was development of the refined test procedure aiming to be able to undertake a similar test with the addition of a heat variable to measure the effect of this. It was expected that due to the material properties of polymers, that high temperatures would severely decrease the force required to compress the pipe to a complete crush.

6.3.1 Material Reaction to Heat

When comparing final crush loads for the different material pipe types it a drastic decrease in required force to crush is obvious. The when comparing the max loads the highest load required was a mere 1400N being the PEX Test 1 and a PVC pipe only required 32N of load to crush it completely. Although these test were not absent of sources for error the sheer difference in force required to crush over all is astounding.

When analysing the results there also appears to be the development of a different crush profile as to what was produced in the refined test procedure and also other external tests on room temperature polymers [8, 35]. In external testing it was stated that there was a distinct profile of linear elasticity, followed by a plateau and then a densification which was also supported by the initial and refined test results. However this appears not to strictly be the case in the high temperature testing.

Looking specifically at the PVC Test 2 compared to Test 3 there are two distinctly different reactions to high temperature and the final effect shown below after the crush. It can be seen that both test follow a similar path up until the 10mm point of extension where Test 1 peaks to a higher force quickly whereas Test 3 continues on a fairly regular trajectory. Test 2 reaches load of 46N then the test piece failed that being the piece broke at the bending points on the side hence the dramatic decrease in load. This is the only piece in all of the test undertaken that had a complete failure or rupture.

Figure 6.7: PVC Pipe Rupture

Viewing the PEX high temperature testing data there is a high level of consistency as to how the pipe reacted to the temperature. The test proceeded as normal where the piece progressively took more load before a failure of sorts happened at the 10 12mm extension point where the pipe buckled under the load. This is likely to be caused by hot spots on the pipe from on uneven spread of heat. It is likely that the point where the normal bend would take place was cooler and therefore could take more load than the piece closer to the heating plate resulting in the bending happening there. All pieces had the same reaction with the final pieces all having the presence of a pinch in the material.

Figure 6.8: PEX Compression Buckling

The HDPE high temperature results were once again fairly consistent with the only variation coming about in the 5-10mm extension point. This peak varied through the tests with particular anomalies coming from Test 2 with the no peak occurring within that range. This was caused by a slight collapse of the pipe. The aftermath is shown in the figure below where the top surface became almost viscous and spread apart instead of holding its form such as the other tests did. This meant the load was felt differently by the pipe and didnt reach quite the heights of the others.

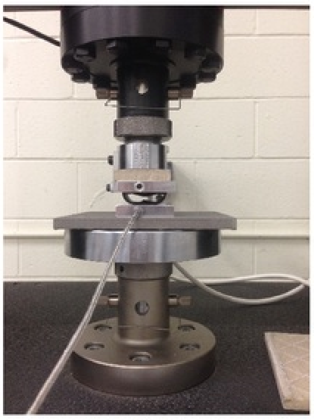


Figure 6.9: HDPE Melting in Compression

Looking at the PEX AL PEX we can see a test that highly resembles it room temperature testing data just with a lower force. This would seem to be linked to the presence of the aluminium layer and how it is effected by heat. Firstly the addition of layers means that the heat has to transfer three different material types. In saying this it would seem that the temperature would be spread morn evenly though out the piece because of the aluminiums heat transfer rate. This would mean less hotspots and therefore less chance of collapse or failure such that occurred in the other high temperature testing. The added strength give to the pipe from the aluminium would be immense due to the little effect that heat has on the material compared to the polymers. Another result of this heat is the piece remained perfectly falte after the test and experienced sligh delamination.

Figure 6.10: Flat PEX AL PEX

Figure 6.11: PEX AL PEX Holding Shape in High Temperature

The heat transfer in the materials due to dimensions must also be considered. Obviously the thicker the wall of the pipe the more time it will take for the heat to spread throughout the pipe. This would mean that the thinner walled pipe i.e. the PVC and HDPE, would be affected more prominently by this heating design and even in compartment fire conditions.

Also looking into the heat spread of the rig this desing is definitely going to create hot and cold spots purely cause of how the rig was desinged. Being a very basic design for high temperature testing this can be expected and understandlably would be effecting the results.

6.3.2 Rig Analysis

Through the results produced, the effectiveness of the rig can also be scrutinised. The aim of the rig was to make able the high temperature testing of polymer pipes. On face value when looking at the results the design of the rig could be granted a success. However the rig was no doubt the source of some error due to slight design limitations.

Through the progressive testing method of the rig meant that instantly the rig would non-intrusive to the testing of the piece. When looking at the progressive test plot all results were very similar and therefore no cause for refinement in the design.

Looking at the success of the rig there was the ability to produced 12 tests of high temperature testing on a range of different material types and different dimensions. The test piece experienced a ramp up heat increase that replicated that of a compartment fire and after that experienced the compression that would be exuded from a Hilti fire stop collar [9, 18]. With the aim of the rig to allow for the mimic of fire conditions on a polymer pipe it could be deemed as successful. It was also shown that the addition of the rig to the Universal Tester was non-invasive, protective to the equipment and allowed for the application of the refined test procedure which was an aim of the design.

When analysing possible problems with the rig, one that was particularly noticeable was the lack of robustness, being that towards the last few tests the rig was not as structurally sound. During testing the bottom tile shattered multiple times, mainly due to constant heating and cooling paired with constant compression. As well as this, the multitude of tests wore out the PTFE bush that allowed for flex in the heating plate and correct transfer of load through the tile and plate. This resulted in the upper heating plate not always sitting level at the start of the heating phase of the test. This ultimately could have affected the initial load exhibited on the piece and therefore the overall results of the later tested pieces.

Another important characteristic of the rig was the expansion due to heat of the aluminium plate. This would have had some affect ton the initial load experienced by each of the heated pieces and possibly cause deformation of the piece before the test started. As expected, the aluminium plate once heated via the cartridge heaters swelled, usually exhibiting anywhere from 1 to 4N on the piece. This does not meet the refined procedure requirements but overall should not have affected the quality of the test significantly.

To address the issues mentioned above the introduction of materials which are less affected by ware would solve the issue of the PTFE slackness during the last few tests or even the ability to quickly replace the piece. Unfortunately, due to the time constraints of the project, this was not able. To address the swelling of the aluminium heating plate a metal could be used with a lesser thermal expansion coefficient or maybe even a change to procedure to allow for the force produced by this expansion. A material that would be a good option could be copper as it also has a higher heat transfer coefficient meaning it would make an equally good heating plate.

Unfortunately a limitation that came about from the rig was the inability to undertake a test with the test piece experiencing the full 180°C. This was as a result firstly of safety considerations, with one test attempted causing smoke to be produced and the plastic coating around the upper heat cartridge starting to melt and burn. This test was stopped early without any compression taking place. It was later attempted for a second time but this test resulted in the lower refractory tile shattering being the second problem, instantly making the test void.

Figure 6.12: Procelain Refractory Tile Fracture

Chapter 7

Conclusion

The purpose of this report was to design a test method to allow for the analysis of the strength of a range of polymer pipe types. This was to be done via the use of an Instron Universal Tester and the development of a test method which primarily addressed the issue of defining an end point of a compression test.

The compression test that was undertaken had to mimic the compression that a Hilti firestop device inflicts on a polymer when activated in compartment fire conditions, that being experiencing a diametral directed load with a temperature of approximately 180°C. Although this was the primary goal to reach, other objectives had to be achieved to allow for this. Those objectives were the production of results for a room temperature crush, the development of a rig that is nonintrusive and allows for application of the developed test procedure.

The procedure produced whilst meeting the required ASTM testing standards also produced high quality results emphasising relationships between different pipe material make ups as well as the ability to relate the length of a pipe to a required force to compress. The similarity of these results in comparison with other previous polymer testing help to legitimise the results with the major discrepancies being related to a differing geometry and not error in procedure.

The successful room temperature testing led to the development of a rig to allow for the high temperature testing. The design ensured that the Instron Universal Tester would not be damaged from testing as well as allowing for non-invasive heat testing. The design of the rig was then progressively implemented and tested meeting all requirements that had been set for it. The quick progression of design testing allowed for the construction of the rig through Macquarie Engineering and Technical Services.

Once the high temperature testing apparatus had been constructed and the necessary safety requirements had been met testing was undertaken on the selection of polymer pipe types available. The results were quite astounding with, in most cases, the force required was immensely less as well as producing failures in some test pieces which had not occurred in room temperature testing. One material that went somewhat against the grain was the PEX AL PEX that still held its shape well under the high temperature compression albeit still requiring a considerably smaller amount of force to crush. The expected immense effects of high temperature testing were surely experienced.

Overall the project met the set aim through the systematic achievement of the objectives set out in the introduction. The new compression procedure developed was effective under room temperature conditions. However when applied to the designed high temperature rig, the production of hot spots occurred affecting the quality of results but still allowing for identification of the decrease in required compression loads from room to high temperatures.

Chapter 8

Future Work

From the data produced in the project it is there is the development of plenty of other avenues that can be followed on into the future. A specific source of future enquiry will be the refinement of the work completed for this project.

Due to the time constraints of this project the testing that was undertaken was only completed on a handful of the individual length and material types. There is an opportunity for this to be developed in the future whether that be through repetitious means i.e. undertaking more tests of the same material and dimensions or expanding the testing method to a wider variety of materials. As well as the expansion of test pieces the ability for continued refinement of there of the developed procedure.

A major opportunity for future work is the continued development and probable redesign of the high temperature testing rig that was produced. Due to the time and monetary constraints of the project the apparatus produced has the ability to be expanded on. Particular advice would be the production of a high temperature testing apparatus that would minimise the production of hot spots during heating while still being able to undertake an instantaneous compression test. The differing temperature in the test piece had a definite effect on how the compression was felt by the pipes and having a consistent temperature though out the pipe would be a great research task to extend the understanding developed through this project.

Chapter 9

Abbreviations

PEX	Crosslinked Polyethene
FRL	Fire Resistance Level
PVC	Polyvinyl Chloride
HDPE	High Density Polyethene
PEXa	Crosslinked Polyethene Peroxide
PEXb	Crosslinked Polyethene Silane
PEXc	Crosslinked Polyethene Radiation
ESCR	Enviromental Stress Crack Resistance
Al	Aluminium
PAP	PEX AL PEX
PS	Pipe Stiffness
SF	Stiffness Factor
OD	Outside Diameter
ID	Inside Diameter
MgO	Magnesium Oxide
DMM	Digital Multimeter
METS	Macquarie Engineering and Technical Services
PTFE	Polytetrafluoroethene

Appendix A

Procedure Images

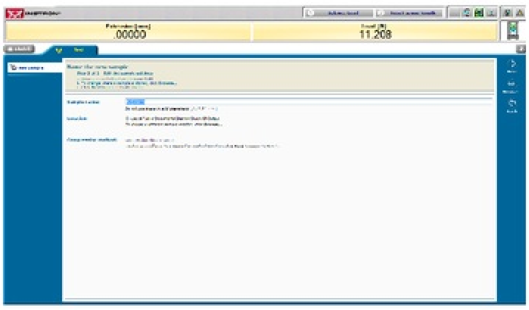


Figure A.1: Intial Instron Test Page

Figure A.2: Set Compression Rate Screen

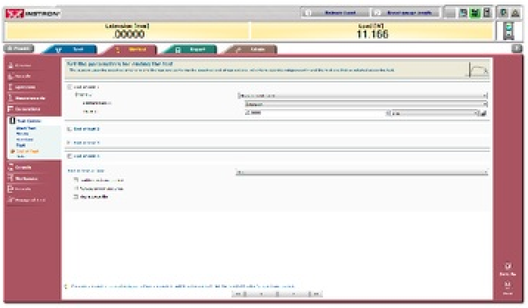


Figure A.3: Set End Point Screen

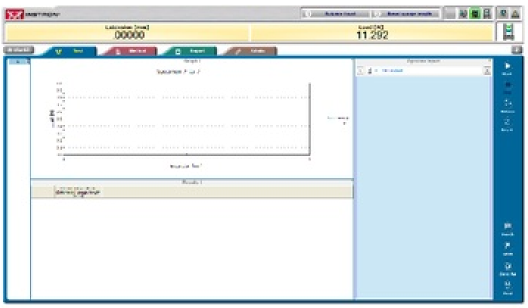


Figure A.4: Test Start Screen

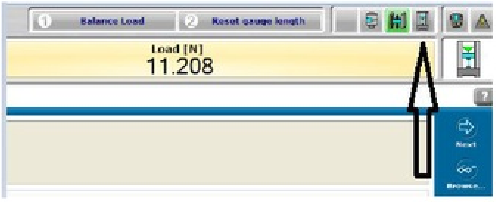


Figure A.5: Calibration Option for Initial Setup

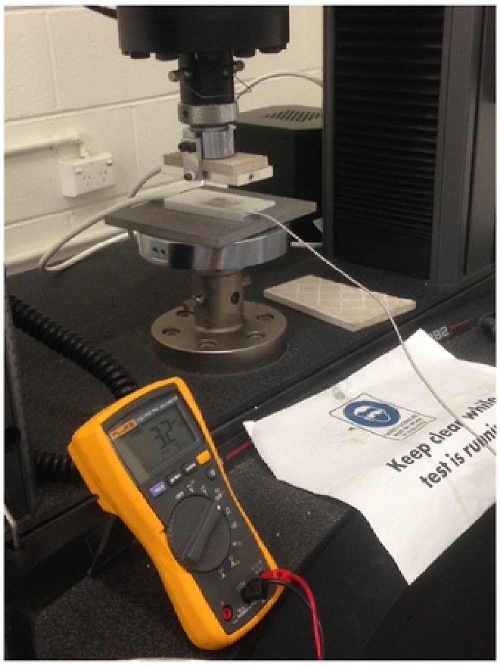


Figure A.6: Rig Set Up Prior Test

Appendix B

Figures of Report

Figure B.1: HDPE Pieces Prepared by METS

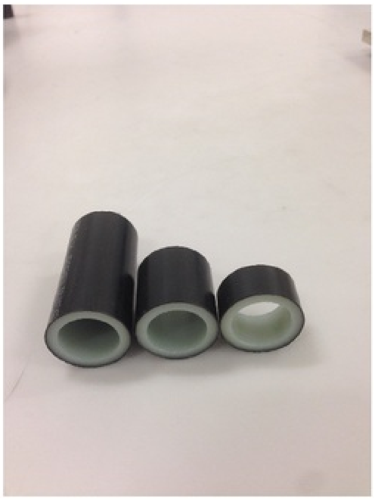
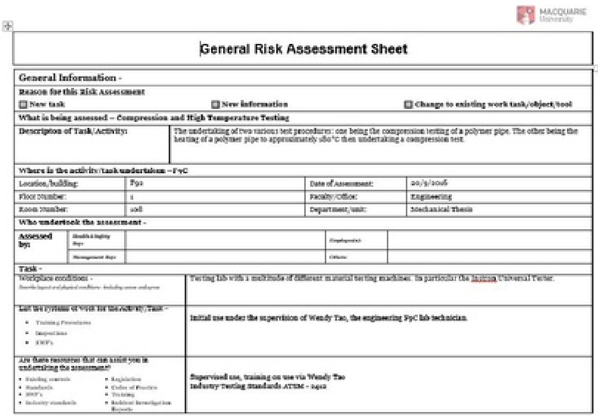


Figure B.2: PEX Pieces Prepared by METS

Figure B.3: PVC Pieces Prepared by METS

Figure B.4: PAP Pieces Prepared by METS



General Risk Assessment Sheet

General Information -

Reason for this Risk Assessment

New task | New information | Change to existing work task/object/tool

What is being assessed – Compression and High Temperature Testing

Description of Task/Activity:	The undertaking of two various test procedures: one being the compression testing of a polymer pipe. The other being the heating of a polymer pipe to approximately 180°C then undertaking a compression test.

Where is the activity/task undertaken – FyC

Location/building:	E92	Date of Assessment:	20/9/2016
Floor Number:	1	Faculty/Office:	Engineering
Room Number:	108	Department/unit:	Mechanical Thesis

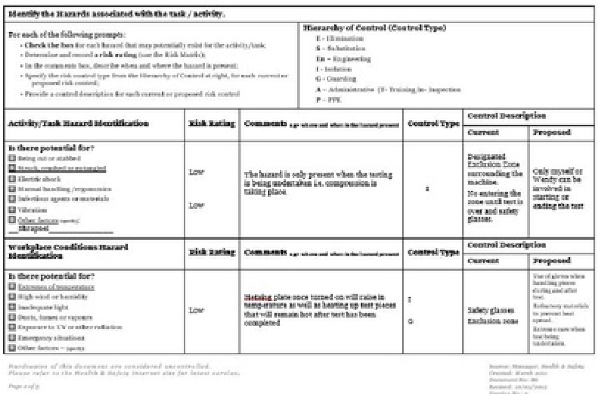
Who undertook the assessment -

Assessed by:

Task -

Workplace conditions -	Testing lab with a multitude of different material testing machines. In particular the Instron Universal Tester.
List the systems of work for the Activity/Task - Training Procedures; Inspections; SWP's	Initial use under the supervision of Wendy Tao, the engineering FyC lab technician.
Are there resources that can assist you in undertaking the assessment?	Supervised use, training on use via Wendy Tao Industry Testing Standards ATSM - 2412

Figure B.5: Risk Assesmnent Part 1



Identify the Hazards associated with the task / activity.

For each of the following prompts:

- Check the box for each hazard that may potentially exist for the activity/task;
- Determine and record a risk rating (use the Risk Matrix);
- In the comments box, describe when and where the hazard is present;
- Specify the risk control type from the Hierarchy of Control at right, for each current or proposed risk control;
- Provide a control description for each current or proposed risk control

Hierarchy of Control (Control Type)

E - Elimination
S - Substitution
En - Engineering
I - Isolation
G - Guarding
A - Administrative (T- Training/In- Inspection
P - PPE

Activity/Task Hazard Identification	Risk Rating	Comments	Control Type	Control Description: Current	Control Description: Proposed
Is there potential for? Being cut or stabbed; Struck, crushed or entangled; Electric shock; Manual handling /ergonomics; Infectious agents or materials; Vibration; Other factors (specify) Shrapnel	Low Low	The hazard is only present when the testing is being undertaken i.e. compression is taking place.	I	Designated Exclusion Zone surrounding the machine. No entering the zone until test is over and safety glasses.	Only myself or Wendy can be involved in starting or ending the test

Workplace Conditions Hazard Identification	Risk Rating	Comments	Control Type	Control Description: Current	Control Description: Proposed
Is there potential for? Extremes of temperature; High wind or humidity; Inadequate light; Dusts, fumes or vapours; Exposure to UV or other radiation; Emergency situations; Other factors	Low	Heating plate once turned on will raise in temperature as well as heating up test pieces that will remain hot after test has been completed	I G	Safety glasses Exclusion zone	Use of gloves when handling pieces during and after test. Refractory materials to prevent heat spread. Extreme care when test being undertaken.

Figure B.6: Risk Assesment Part 2

Figure B.7: Test Pieces Post Compression

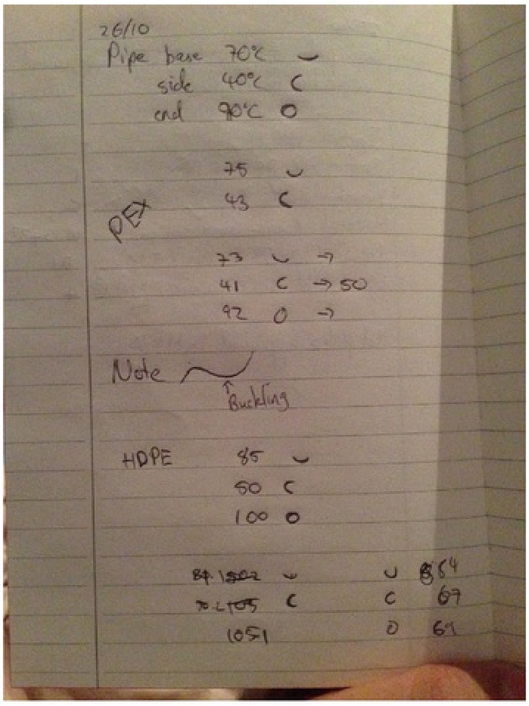


Figure B.8: High Temperature Heat Readings 1: Internal Top, Internal Side and Post Test

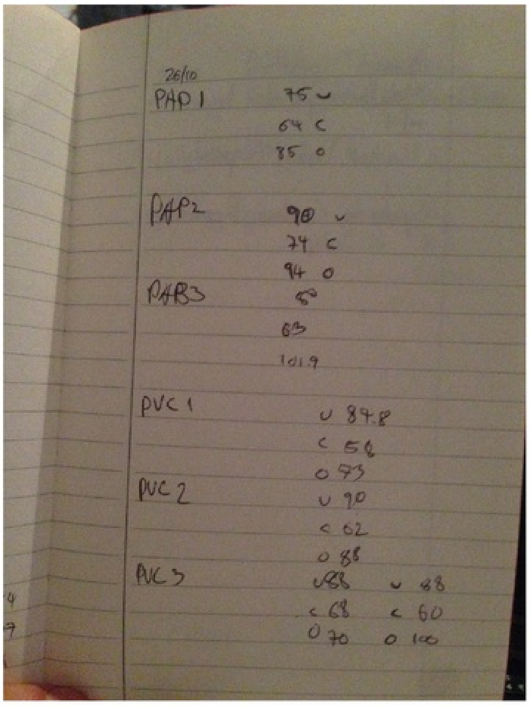
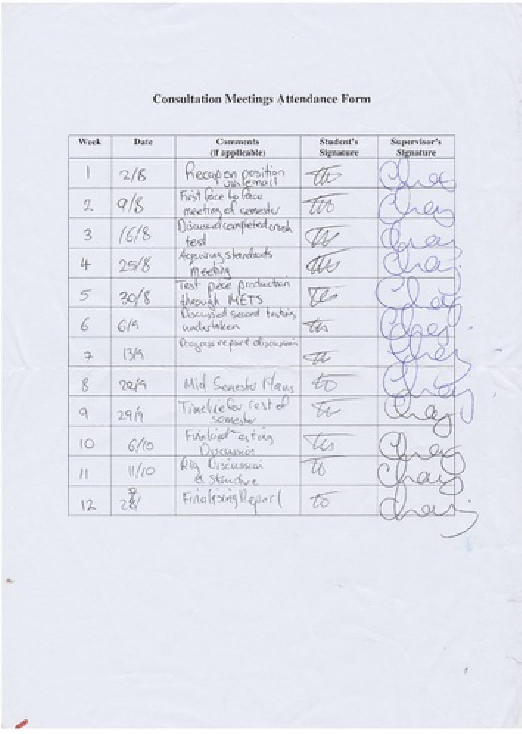


Figure B.9: High Temperature Heat Readings 2: Internal Top, Internal Side and Post Test



Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	2/8	Recap on position w/ email	[illegible]	[illegible]
2	9/8	First face to face meeting of semester	[illegible]	[illegible]
3	16/8	Discussed completed crash test	[illegible]	[illegible]
4	25/8	Acquiring standards meeting	[illegible]	[illegible]
5	30/8	Test piece production through METS	[illegible]	[illegible]
6	6/9	Discussed second testing undertaken	[illegible]	[illegible]
7	13/9	Progress report discussion	[illegible]	[illegible]
8	22/9	Mid Semester Plans	[illegible]	[illegible]
9	29/9	Timeline for rest of semester	[illegible]	[illegible]
10	6/10	Finalised testing Discussion	[illegible]	[illegible]
11	11/10	Rig Discussion & Structure	[illegible]	[illegible]
12	28/	Finalising Report	[illegible]	[illegible]

Figure B.10: Weekly Supervisor Meeting Sheet

Appendix C

Refined Room Temperature Stress vs Strain Plots

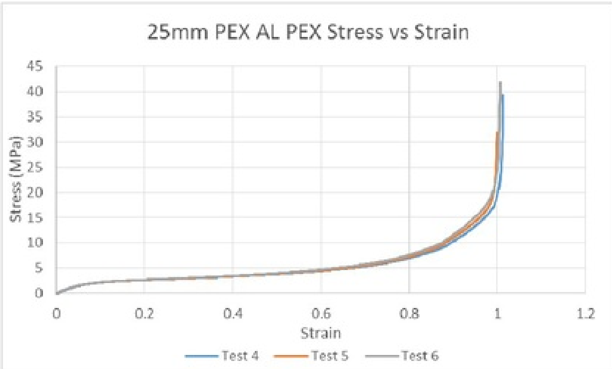


Figure C.1: 25mm PEX AL PEX: Stress vs Strain

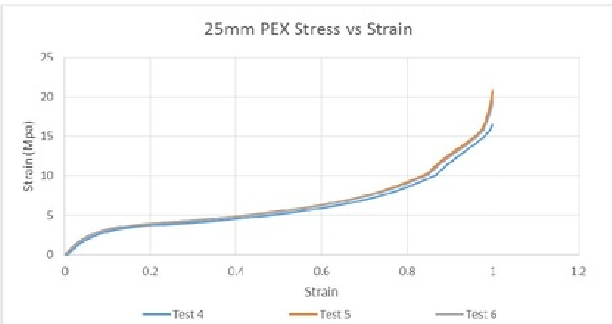


Figure C.2: 25mm PEX: Stress vs Strain

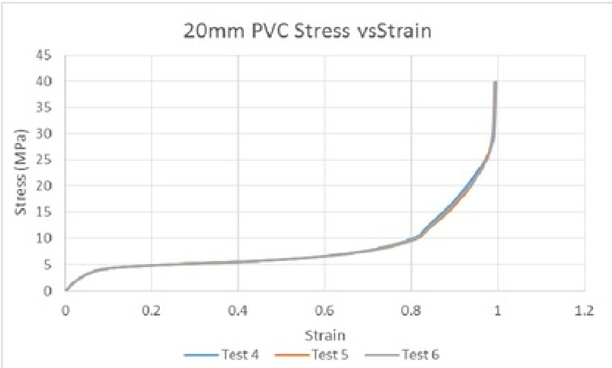


Figure C.3: 20mm PVC: Stress vs Strain

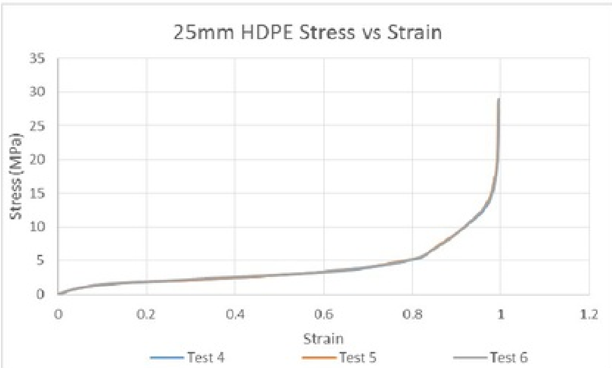


Figure C.4: 25mm HDPE: Stress vs Strain

Bibliography

[1] "Thermoplastics vs.thermosets: An introduction," 2015. [Online]. Available: http://plasticnotes.blogspot.com.au/2010/04/thermoplastics-vs-thermosets.html

[2] "Extrusion of plastics," 2014. [Online]. Available: http://www.mechscience.com/extrusion/.

[3] *Tested Applications: - Retrofit for Plastic Wall Pipes*, 1st ed. Hilti, 2005. [Online]. Available: https://www.hilti.com.au/medias/sys_master/hd0/h06/9116125233182.pdf

[4] P. Sharpe, "Making plastics: From monomer to polymer — aiche," 2015. [Online]. Available: http://www.aiche.org/resources/publications/cep/2015/september/making-plastics-monomer-polymer.

[5] *Crosslinked Polyethylene(PEX) Pipe and Tubing*, 1st ed. Plastic Pipe Institute, 2013. [Online]. Available: https://www.plasticpipe.org/pdf/tn-17_crosslinked_polyethylene_pex.pdf

[6] "Organic chemistry- definition," 2016. [Online]. Available: http://chemistry.tutorvista.com/organic-chemistry.html

[7] "Crush strength and flexibility of thermoplastic piping." [Online]. Available: http://www.ppfahome.org/ub1.aspx

[8] M. Avalle, G. Belingardi, and A. Ibba, "Mechanical models of cellular solids: Parameters identification from experimental tests," *International Journal of Impact Engineering*, vol. 34, no. 1, pp. 3–27, 2007.

[9] W. Zhao, R. Zong, J. Liu, J. Ye, and K. Zhu, "Study of the fire characteristics for multi-source fires in the confined corridor," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 147, pp. 239–250, 2015.

[10] "Cartrige heaters," 2016. [Online]. Available: http://www.asbheat.com/01_html/products/08_cartridge_heaters.shtml

[11] R. Cobden, Alcan, and Banbury, *Aluminium: Physical Properties, Characteristics and Alloys*, 1st ed. TALAT, 1994. [Online]. Available: http://core.materials.ac.uk/repository/eaa/talat/1501.pdf

[12] S. Asadi, H. Babaizadeh, N. Foster, and R. Broun, "Environmental and economic life cycle assessment of pex and copper plumbing systems: A case study," *Journal of Cleaner Production*, vol. 137, pp. 1228–1236, 2016.

[13] K. Bachner, "Piping for new construction plastic vs copper," 2016. [Online]. Available: http://healthybuildingscience.com/2015/10/30/piping-for-new-construction-plastic-vs-copper/

[14] A. Radoszewski, "Plastic or metal pipes: Pros and cons," 2007. [Online]. Available: http://cen.acs.org/articles/85/i43/Plastic-Metal-Pipes-Pros-Cons.html

[15] R. O. D. J. Jonsson, "Cause of copper corrosion in plumbing systems," 2007. [Online]. Available: http://www.fwr.org/copper.pdf

[16] T. Martin, "Polymer pipes under fire conditions," *Hilti - Rhodes Australia*, 2016.

[17] D. O'Leary, "Polymerisation," 2000. [Online]. Available: http://www.ucc.ie/academic/chem/dolchem/html/dict/polymers.html

[18] "Pe pipe and fittings manufacturing," 2015. [Online]. Available: https://plasticpipe.org/pdf/chapter04.pdf

[19] "Thermoplastics - physical properties," 2016. [Online]. Available: http://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html

[20] *Protection of Openings the Penetrate Fire Rated Elements*, 1st ed. Building Codes - Queensland Government, 2004. [Online]. Available: http://www.hpw.qld.gov.au/SiteCollectionDocuments/180.pdf

[21] *Firestop Code Overview*, 1st ed. Hilti- Firestop Specifications, 2015. [Online]. Available: https://www.hilti.com.au/medias/sys_master/hd6/h06/9116125429790.pdf

[22] "Technical fibre products," 2012. [Online]. Available: http://www.tfpglobal.com/materials/intumescent-materials/

[23] "Intumescent technology and fire engineering," 2016. [Online]. Available: http://www.astroflame.com/intumescent.html

[24] P. Lepoutre, *The Manufacture of Polyethylene*, 1st ed., 2006. [Online]. Available: http://nzic.org.nz/ChemProcesses/polymers/10J.pdf

[25] *Chapter 4 - Pe Pipe and Fittings*, 1st ed. Plastic Pipe Institute, 2015. [Online]. Available: https://plasticpipe.org/pdf/chapter04.pdf

[26] S. Tambooli, S. Mhaske, and D. Kale, "Crosslinked polyethylene," *Indian Journal of Chemical Technology*, vol. 11, pp. 853–864, 2004.

[27] "Material properties - pvc properties," 2013. [Online]. Available: http://www.vinidex.com.au/technical/material-properties/pvc-properties/

[28] R. Klein, *Laser welding of plastics.* Wiley-VCH, 2012.

[29] "Alupex - product catalog - multilayer pipe," 2016. [Online]. Available: http://www.gfps.com/appgate/ecat/common_flow/100005/COM/en/109868/109929/index.html

[30] *Couta Brochure - GASPEX*, 1st ed. The Couta Group, 2013. [Online]. Available: http://www.waterpex.com.au/pdf/couta_brochure.pdf

[31] "Standard test method for determination of external loading characteristics of plastic pipe by parallel-plate loading," *DD2412 -11*, 2011.

[32] "Standard test method for determining dimensions of thermoplastic pipe and fittings," vol. D2122 15, 2015.

[33] "Standard terminology relating to plastic piping systems," vol. F412 16, 2016.

[34] D. Roylance, "Stress-strain curves," *Department of Materials Science and Engineering Massachusetts Institute of Technology*, 2001.

[35] G. Vladimir, "Testing and application of new phenomenological material model for foam materials," *Posterus*, 2010.

[36] "Manufacturing process and technical classifications," *Institut De Promocio Ceramica*, 2016.

[37] W. Dultra and E.Acchar, *Ceramic materials from coffee bagasse ash waste.*

[38] "Hi-density cartridge heater features - cartridge heater brochure," 2014. [Online]. Available: http://www.tempco.com/Catalog/Section%202-pdf/Hi-Density.pdf

[39] "How do thermocouples work?" 2016. [Online]. Available: http://www.explainthatstuff.com/howthermocoupleswork.html.