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Investigation into the process of cured-in-place pipe sewer rehabilitation

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Abstract

Sewer networks affect the entire world with the ability to bring clean streets to cities which may otherwise be completely disease-ridden. Ageing sewer networks present a problem, but new technologies are paving the way for rehabilitation. Trenchless repair options such as CIPP (cured-in-place pipe) liners are one such option. This paper aims to evaluate the full process that precedes and proceeds the installation of a CIPP liner for the rehabilitation of a defective sewer with the aim of finding potential solutions to the current concerns and to streamline the full CIPP method. Further inspection was conducted into the testing practises for CIPP liners to see any fundamental failures and their impact on failure behaviours. Primarily thickness, flexural strength testing and electron microscopy imaging has been carried out with results showing a large range of differences between samples in all aspects of testing. The focus for improvement based off analysis of the testing leans toward creation of a data management tool which would make all sewer pipe data accessible from one source, helping streamline processes and ensuring the features of the pipe were up to-date alongside documenting and recording any work that has been completed.

Introduction

Read and Vickridge (1997) define a sewer as ‘an underground conduit or duct formed of pipes or other construction used for the conveyance of surface, sub-soil or waste water’. Sewers have become an everyday piece of infrastructure, South West Water alone provide services to 1.7 million customers throughout their district in 2018 (South West Water, 2018). With the length of sewers across the country estimated to be approximately 302,000km in 2001 (Davies *et al.*, 2001). Ferriman (2007) stated that sewerage disposal had been voted as the most important medical milestone since 1840 by more than 11,300 British Medical Journal readers.There are many elements that create a wastewater system, including manholes, sewers, pumping stations and treatment works. This research will focus on combined wastewater sewers which collect effluent and storm water (Linsley *et al.*, 1992).

This paper aims to investigate a commonly used repair method for sewers, CIPP (cured-in-place pipe) lining systems. Berglund *et al.* (2018) state that over 40,000 miles of sewer pipes have been repaired using this system throughout the world. Through this research the entire process of CIPP installation will be analysed, inclusive of prioritisation, surveying, allocation of repair type, installation, testing, maintenance and end of life. However, focus will be based on testing which will include experiments on CIPP lining samples to establish their average wall thickness, flexural strength and electron microscopy imagining.

Background Information of Sewer Networks

Sewers style networks have been traced back to 4000 BC, however these were considerably different to modern day sewers and usually consisted of drains in the street. More complex underground drainage was first established in Crete around 3000 BC (De Feo *et al.*, 2014), with modern societies beginning to use pipe type structures to transport water in roughly 5700-3000 BC (Angelakis & Zheng, 2015). When the Roman Empire took hold of the western world from approximately 750 BC until 480 AD (Mark, 2018) (De Feo *et al.*, 2014), Europe benefit significantly from increased access to free ‘safe’ drinking water and increased sanitation thanks to Roman engineering advances (Radova, 2015) which materialised once the Romans started to explore the link between water quality and health. The first modern sewer network built by the Romans, was referred to as the Cloaca Maxima (Lofrano & Brown, 2010). It was based on an open canal system which developed to contain buried brick sewer pipes throughout the city. As Rome grew, the Cloaca Maxima spread out and more ducts branched off, as well as existing parts of the network being replaced and repaired as required (Hopkins, 2007).

After the fall of the Roman Empire, Europe went into a period of regression (Angelakis & Zheng, 2015), although De Feo *et al.* (2014) discuss that some sewers and aqueduct systems continue to work despite poor maintenance and degradation. However, most sewer systems and sanitation systems fell into disrepair (Coates-Stephens, 1998). Due to the regression, by the end of the nineteenth century there was still 77% of Italy without sewers (Lofrano & Brown, 2010). In 1858 sewer evolution had its next push, thanks to the 1858 London Stink event, which highlighted the effects of poor sewerage systems. That summer was particularly hot, and the Thames was being used as a dumping ground for human effluent, dead animals and rotting food (Burns, 2018). Prior to this summer, Snow had discovered the link between waterborne germs and the spread of cholera, but it wasn’t until 1858 when people started to believe his findings (Siegel, 2017). It was the combination of Snow’s hypothesis and the stink reaching government buildings that finally allowed Joseph Bazalgette to proceed with his drainage plan for London (Halliday, 2001). Bazalgette's London sewer network comprised of 82 miles of main sewers, two treatment works, four pumping stations and river embankments to reclaim 52 acres of land (Halliday, 2012). Bazalgette's system was revolutionary and almost single handily removed cholera from London, further proving Snow's theory (Halliday, 2001).

Up until this point in history there was minimal need for sewer repairs, aside from the Romans doing minimal patch style repairs on their network (Hopkins, 2007). Little is known outside of the Roman repairs about how our predecessors repaired their sewer systems, whether that meant they usually abandoned sewers when they became ineffective or whether they had their own rehabilitation methods, it is unclear. Comparatively, ancient sewer networks are drastically more long-term thinking than their modern-day comparatives which are only designed for a 50-years lifespan (BS EN ISO 112964-4:2018, 2018), whereas some ancient Roman sewer systems are still functional today, over 1500 years after their construction (Angelakis & Zheng, 2015). This may contribute as to why there is little known about historic types of repairs, they could have just not been very common due to lower population, less road traffic, different construction methods and less extreme weather.

Background information of CIPP lining

As previously stated, there is little information regarding historic methods of repairing sewers aside from small amounts concerning Roman hand repairs. Modern times have seen the creation and expansion of the CIPP lining and trenchless repair movement. Moving away from traditional methods of excavation towards manhole access repairs for underground water and sewer pipes. CIPP lining was first established in the 1971 (Berglund *et al.*, 2018), created by an agricultural engineer to fix a leaky pipe. The access to the pipe was challenging and that's when Eric Wood (founder of Insituform – CIPP provider) came up with the CIPP solution to battle the accessibility concerns. The primary purpose of the CIPP liner was to fix a pipe to an acceptable standard without having to replace it. Wood carried out a process which has differed little in the last 48 years, he impregnated a felt tube with a polyester resin, dragged it into the pipe, blew it up and let it cure ambiently. Tests completed on that pipe 30 years later still showed that the strength exceeded the UK standard by almost 30% (Bueno, 2011).

Consequently, Wood was able to create a system that revolutionised the way we repair pipelines today. The introduction of the CIPP product also created other markets such as: CCTV surveying, lateral cutters and curing methods. It has been used to solve issues with infiltration, cracking and even pipes that have been partially collapsed. CIPP has since been the way to repair sewers and pipelines, the benefits far exceed other methods and the list is not limited to: being cheaper, less disruption, being faster, creating a better-quality pipe and requiring less access (What is CIPP, 2019).

Testing of the CIPP liners, began in Insituform with the testing of the first pipe repaired by Wood in 1971. Today, IKT (Institute for Underground Infrastructure, Germany) are at the forefront of testing CIPP liners from throughout Europe, conducting a study each year (Liner Report) which shows samples tested against 4 criteria (flexural strength, water tightness, wall thickness and Young's Modulus). IKT have recently announced that although trends for the last 10 years have been improving, it created questions about the overall quality which has declined slightly over the last few years. The concern has been raised that there might not be enough of an emphasis placed on testing to keep up with quality control checks and Standard requirements.

CIPP Process Technique

The CIPP lining process is used to repair defective gravity pipelines, they commonly repair a stretch of pipe between 2 access points, usually manholes.

1) Pipe Preparation
   a. The pipeline must be blocked and can't be used for service during the installation. A bung or water pump may be used.
   b. The pipeline is then cleaned, using a high-pressure jet washer.
   c. Any sharply edged connections or defects are cut back using a robotic cutter.
   d. Occasionally areas require separate localised repairs before the whole pipeline can be lined.
2) Liner Preparation
   a. The liner is made from a mix of polyester needle felt or glass fibre mixed with a polyester, vinyl ester, epoxy or silicate resin.
   b. The two components are mixed together using a vacuum pressure method (within a factory setting) to ensure full saturation is achieved.
   c. A coating is given to the liner to protect it during transportation.
   d. Depending on the type of resin, UV, hot water, steam or ambient cures are possible, each requiring specific storage criteria.
3) Installation
   a. The liner is winched into place, using manholes as access points.
   b. It is then inflated using water or air.
4) Curing

   N.B Depending on the type of resin used, different processes are required. (Assumptions made for UV cure – common curing method in UK).

   a. Once the liner is in place, a light train is passed through.
5) Post cure
   a. Samples for testing can be extracted, usually from the ends or the interim manholes.
6) Lateral Connections
   a. Using a robotic cutter, reopen later connections.
7) Re-establish flow and return to working order.

The whole process can be completed within 1 working day. Wirahadikusumah *et al.* (1999), gave CIPP a rough cost of $1558/m (£1195 according to XE Currency Convertor). However, it is likely that the meter unit cost has varied considerably in the last 20 years as equipment and processes become more mainstream.

Literature Review

Current situation

Within the UK, the sewer network is thought to consist of over 624,000 km worth of pipes, collecting over 11 billion litres of waste water every day (Defra, 2012). Areas of the country are working to bring their sewers up to modern standards by reducing pollution, repairing sewers and building new treatment works. Currently there are many challenges facing the wastewater networks including maintenance, repairs, environmental pressures and budget (Hlavinked *et al.*, 2008).

When water companies look to review sewer systems it is common to prioritise the sewers which require immediate action. There are various methods for prioritising sewers, different water companies and consultancies usually use different protocols.

Steffens (2018) discusses the need for having long-term plans in place for replacement programs, agreed by Moran (within Hlavinked *et al.*, 2008). Moran (2008) discusses the way pipes can be prioritised based on failure rate, location, age etc. which can save water companies money and time in the long-term. A holistic approach to prioritisation may be more appropriate for many water companies, using cost-benefit analysis, and looking at the pipe data (Wirahadikusumah *et al.*, 1998). Yoo *et al.* (2014) discuss a method for considering the hydraulic importance of the pipe whilst prioritising. However, the most accomplished way of looking at the decision-making process involved in prioritisation may come from Tscheikner-Gratl *et al.* (2017) which compares 5 of the most common MCDM (Multi-criteria decision-making) methods of prioritisation. They discuss the complex interactions between water systems and the different criteria that could be considered by a system. However, it seems irrelevant which process is the 'best' for the decision-making procedure if the information being put into the MCDM system is incorrect.

The industry is also facing problems surrounding access. Contractors must battle with transport, businesses, pedestrians and residents to access manholes (Read & Vickridge, 1997). Even when access is achieved, the methods used for surveying sewers, typically CCTV cameras attached to a rig, can have issues with quality of the CCTV video. Additionally, it is a subjective exercise for the technician to assign defects along the pipe when they consider them adequate for a defect code (Wirahadikusumah *et al.*, 1998). Although times have moved on since Wirahadikusumah *et al.* (1998) made their comments regarding the CCTV quality, those concerns continue in practise today. There are other ways to survey sewers, such as Electro Scans, which can identify areas of infiltration that may get missed during standard CCTV checks (Water Research Centre Limited, 2018), although higher quality surveying equipment usually comes with high cost.

There is also pressure on water companies to ensure they keep up with the environmental demands. This has led to a change in the way that sewers have been repaired, moving away from excavation methods, towards trenchless process which can use manhole access to repair common sewers defects. Hinte (1994) discusses the benefits of this evolution, reducing traffic disruption, noise, public risk to excavation etc., as well as the impact of roads and pathways on being cut for excavations. Tomczak & Zielinska (2017) discuss different rehabilitation options which range from general maintenance to full line replacements. Specifically, Tomczak & Zielinska (2017) highlight the differences between trenchless and open cut techniques for repairing sewers. Trenchless repairs can cover CIPP (cured-in-place pipe), pipe bursting, local patch repairs, jetting and robotic cutting, any repair that can be completed without digging, leaving open cut to cover any excavation-based repair.

Wirahadikusumah *et al.* (1999) discuss the different repairs available and their costs and disruptions, the costliest (of those commonly used in the UK) being open cut. Open cut excavation costs are estimated, at roughly $1804/m (£1383) compared to CIPP lining costing $1558/m (£1195) (Wirahadikusumah *et al.*, 1999). However, through experience, the cost difference is usually higher, due to the extra disruption caused through dig-and-replace schemes. There are also the hidden costs to consider, such as reinstatement of pathways and the increased damage to pathways and roads which makes them more likely to need repairing in the long term (Hinte,1994). The research conducted by Wirahadikusumah et at (1999) was also completed almost 20 years ago, therefore, some techniques are likely to have become cheaper. Gupta *et al.* (2001) found that trenchless repairs can cost up to half the cost of excavation repairs, as well as having the benefits of less disruption to locals etc. Chandrasekaran & Ibrahim (2001) discuss the potential occurrences that would lead towards an excavation repair rather than the trenchless option. Within the UK it is common for companies to shy away from excavation even at extra expense, due to its benefits (Tregoing, 1996).

Environmentally, excavation style sewer renovations have been found to have a carbon footprint of between 4-8 times higher than that of a trenchless CIPP liners (Berglund *et al.*, 2018). The results depend highly on the size of pipe, location, depth of replacement etc. so, there may be too many variables to be able to compare the environmental impact with a high level of accuracy (Muraoka & Wada, 2008). Berglund *et al.* (2018) shows that although CIPP is the better environmental option, it performs worse in 4 out of 18 factors, showing room for improvement. Regardless of any downfalls CIPP lining may exhibit, worldwide, around 65,000km (over 40,000 miles) of sewers has been repaired using CIPP technology (Berglund *et al.*, 2018).

There are different British Standards which highlight ways to install, test and maintain rehabilitation methods (British Standards Institution, 2018; 2013). Although, it could be argued that these standards do not give adequate guidance and there could be a higher level of explanation. Overall, water companies across the UK are actively trying to reduce the likelihood of sewers failing, these have included privatisation of sewers across Wales and England and upgrades to sewer networks and treatment works (DEFRA, 2012).

Other countries

As well as looking at UK repair and renovation options, there is plenty to be learnt from how other countries across the world treat their sewer systems. Throughout the world there is a move towards trenchless technology over excavation. In Malaysia, engineers are exploring more trenchless techniques to move away from the high level of disruption that is contributed to excavation (Gupta *et al.*, 2001). Germany continues to be an engineering hotspot for development. The IKT liner report (2017) showed a high number of Germany companies, which indicates that German companies are beginning to see the benefits of testing and being accountable and public with their progress, a lesson that UK companies may be able to benefit from.

In terms of less advanced sewer networks, Poland's sewer system is in a bad technical state throughout the country and thus a rebuild of their network is beginning. However, due to political difficulties there are delays in making owners keep their sewers in a functioning state (Kolonko & Madryas, 1996). Nevertheless, the infancy of Poland's sewer network could give the rest of the world an insight into modern systems. Finland has had a history of poorly effective sewers, leading to high levels of sickness, due to sewers discharging waste too close to water intake points (Juuti *et al.*, 2008). Juuti *et al.* (2008) discuss the benefits of moving away from short-term thinking and the advantages of long-term management, maintenance and rehabilitation being in place. Mostly, countries are moving together towards trenchless repairs being the main form of rehabilitation. There is also a common theme that long-term strategy and trenchless repairs have been recognised as the best solutions to deal with sewer networks.

Success criteria of sewer systems

As time progressed some of the Victorian sewers have deteriorated to fail. Wehner (2006) discusses the main concern for modern-day sewerage fail which could see a repeat of the 1858 Great Stink, leading onto the question of what defines a successful sewer and, what failures mean for the overall sewer network.

It would be simple enough to state that a 'good' sewer needs to collect waste and move it along to a treatment plant or destination. However, there are other criteria that should be considered when establishing if a sewer has fulfilled its purpose.

There are two main types of failure throughout infrastructure, known as SLS (service limit state) and ULS (ultimate limit state) failures. Sewers also have SLS and ULS failures which occur which include cracking and infiltration etc. (Wirahadikusumah *et al.*, 1998). The damage sustained to sewer networks is explored by Ridgers, Rolf & Stål (2012), these can cause problems including flooding. Soil conditions can affect networks due to voids in the soil causing defects which can lead to collapse. There is also a considerably higher chance of sewers over 25 years old getting defects (Karoui *et al.*, 2018). All of which could cause defects which could require a liner to be installed.

Davies *et al.* (2001) specify a list of points they consider 'basic performance requirements', which include: pipework not blocking, safeguarding, health and safety, reduced pollution, structural and design life and reduced odour and toxicity. These key objectives have been paraphrased from BS EN 752-2 (1997) however, since its publishing it has been superseded with a more extensive list of requirements which give larger emphasis on the environment and sustainability criteria (BS EN 752, 2017).

BS EN 752:2017 (2017) splits the requirements for a sewer network into four key areas which include: hydraulic performance, structural, operational and environmental requirements. Therefore, it could be argued that if a sewer were to fail on any of these points it would be considered a failure, regardless of whether the sewer still technically functioning in carrying wastewater. These points create an interesting level for CIPP to be measured against, to see if CIPP liners are effective at reaching the 'gold standard'. Consequences of failures within sewers vary considerable depending on the failure, they can be carried socially, economically and environmentally. These include, and are not limited to: delays to traffic, disruption of local economy, flooding of residential and business properties, health consequences, environmental impacts and smell, noise and dirt (Davies *et al.*, 2001). Lamond, Proverbs & Hammond (2008) estimated that over £200 billion worth of assets are at risk of flooding throughout the UK.

Notably, there are many types of failure that the world must contend with, for example: earthquakes, landslides, extreme weather and natural disasters (Hlavinked *et al.*, 2008). However, this paper will be focusing on issues common to the UK. The CIPP lining process naturally follows the same recommended criteria. However, it's worth considering some of the few limitations to the method.

Hauck and Wear (2011) discuss a CIPP failure and it's causes, which resulted in 330 feet of CIPP being removed and reinstalled. This was due the CIPP liner wall being thinner than the recommended thickness, as well as ineffective and damaging repair methods trying to patch the initial crack failure. The report mentioned that there was dramatic change in the gradient of the pipe which caused issues when installing the CIPP. This meant that there to be 2 installs which were joined later. Usually, that would not be of concern, but the amount of grout used was higher than recommended, which caused a bulge in the liner. It could be summarised that this failure was caused by a lack of knowledge into how best to first repair the defects of the liner.

Alongside the gradient limitation, the same can be said for changes to diameter or shape. The changing from one to another causes a difficult seam for the CIPP liner to attach to, and therefore could cause a bulge which would more susceptible to defects.

CIPP liners are very versatile, they can be used to fit various shapes, a large range of diameters and have reached 900m lengths in one installation. Naturally, they require good access manholes which commonly are surveyed prior to rehabilitation being done on the line to ensure the access points are adequate for the CIPP liner to be installed from.

This research

Throughout the evaluation of literature, there have been references to possible improvements and ways to increase the efficiency of the current processes. Within this paper, those improvements will be explored, including: exploration of the full life cycle of CIPP liners; a critical look at current rehabilitation methods available, including their environmental impacts and disruption factors; examination of current British and International Standards governing sewer repairs; and an exploration into possible standardised method for assigning rehabilitation options to defective pipes. To assess the mechanical properties of the liners, testing will be completed based on current British Standards for tests (British Standards Institution; 2013, 2015, 2018), including experiments to judge Young's Modulus, wall thickness and flexural strength, in line with IKT's international standard based sewer tests (IKT, 2017). Electron Microscopy imaging will also be completed, giving a magnified view on the sample and its components. Each of these sections will have a clear methodology, results and discussion section in order to clearly outline their individual impact on the research.

A deeper look into the guidance given by the British Standards Institute and their international equivalents will aim to provide potential gaps, these could possibly give space to update boundary conditions to modern day need, which could increase standardisation of installation, maintenance and expectation of sewer repair systems. Finally, bringing together British and International Standards, industry knowledge and further research, it may be possible to create a consistent algorithm for sewer surveyors and engineers when attaching defect codes to sewers and repair options to respective defects to reduce human error and increase efficiency.

In conclusion, there are many aspects of sewer rehabilitation methods that will be explored during this examination, with the main aim of helping the industry to see other ways to increase the sustainability and longevity of repairs throughout the sewer networks, in addition to trying to find new ways to slim down the whole process of installation. This could potentially show ways for companies and utilities to reduce cost, time and resources.

Process Breakdown

Although companies are battling modern day issues, there continues to be more problems along the way. It's become apparent that a large proportion of repaired sewers haven't been tested to an adequate level (WWT, 2014). As discussed, this paper aims to briefly look at the whole process of CIPP with a focus on testing aspects of the process. The problems can be summarised by need for data to help make the process autonomous in the future, software such as the WinCan, which has the capacity to incorporate the life cycle of the sewer line in a user-friendly format.

Prioritisation

Prior to any work being completed, the elements must be prioritised. This ensures high risk components get reviewed quickly, reducing the impact to infrastructure. Common characteristics considered include: location, length, diameter and age etc.

As previously discussed, there are many ways companies will choose to prioritise which sewers require surveying. These are largely algorithmic based process which consider information of the component and allocates a criticality score. Steffens (2018) highlights the need for long-term planning for prioritisation to utilise resources and finances. There is a recommendation from industry to use a system that considers different characteristics of the pipe. Currently, it's likely that the sewer will be prioritized based on when the line was last reviewed, rather than on the pipe features.

Tscheikner-Gratl *et al.* (2017) review different MCDM tools to find the 'best' solution in reviewing sewer, water and gas pipelines. They consider different characteristics of the pipeline, covering physical characteristics and external criteria. These cover the following features: shape, length, depth, material, age, diameter and location. The external factors considered are ground water level (GWL), climate, traffic etc. They also consider the proximity of the pipeline to infrastructure, in relation to costs and/or vibration effects. This range of characteristics enables the MCDM to be holistic.

TOPSIS was highlighted as the only MCDM without drawbacks in a study completed by Siksnelyte *et al.* (2018) when comparing 8 different processes for decision making, however, AHP was deemed to only have the disadvantage of requiring validation which is likely to be a requirement regardless of the type of MCDM used. Therefore, the simple AHP system is recommended to introduce the industry into a more structured format which can be taught quickly.

The basic principle of the MCDM process for value measurement includes having a weighting score for each element of the pipeline. The attached weighting scores then get combined to give a final prioritisation mark. Based on alternative methods, which include goal focused and outranking methods, this seems the simplest way of combining all elements of the pipes (Tscheikner-Gratl *et al.*, 2017). The alternatives require further information to be created regarding the 'goal' being aimed for by the decision-making process, which wouldn't be as appropriate in this situation.

The accumulation of this information can then be put onto a map, showing the location of each severity level. The maps then make it easier to create work orders for contractors to survey the critical pipes. It has been suggested that a simple structured value measured AHP system would be the best solution to prioritise sewer lines based on the advantages discussed by Tscheikner-Gratl *et al.* (2017), which also consider the holistic approach recommended by Steffens (2018) and can be evolved to include the hydraulic requirements discussed by Yoo *et al.* (2014). One of the main benefits of this system is the level of accountability. Using a system which comes from a standard structured approach ensures a rational look into each problem, consistent and objective outputs and repeatable and reviewable decisions. It highlights the accountability trail through the process, with a document trail being able to be built into the system, any concerns or reviews that are required later can then be checked and responsibility and accountability can be associated, ensuring the process remains efficient and reliable.

However, this whole process is dependent on the information being inputted into the AHP algorithm and therefore requires good quality data to be effective. Therefore, it's the recommendation of this research that although a future prioritisation tool requires development to ensure all physical and external criteria are met, it also requires correct information, which can only be achieved and verified commonly through surveying the lines and updating the existing information. Therefore, the focus should be to update and verify the information already being held to ensure the best quality data is being used for the prioritisation tool, which will improve the process in the long-term.

Naturally, the impact of getting the prioritisation tool wrong is that a part of the sewer network may be overlooked and would be open to three possible options: either the sewer would be checked eventually and be found to be functioning adequately, it would be checked and would require higher level of repair than if it had been checked earlier and the sewer pipe failed and would be causing issues alerting to its failure, by which point it's likely that a full excavation may be the only means to repair. Therefore, methods to ensure the correct sewers are surveyed and repaired is of crucial importance financially, environmentally and in the best interest of the public.

Surveying

CCTV quality is crucial in determining defects along a pipe. Plihal *et al.* (2015) remark that sewer systems are often not surveyed for 10 to 15 years or until they have caused issues such as flooding triggered by severe defects. However, before a survey can even begin, the pipe must be found. That may seem a very straight forward task, although it is common for drawings to be out-of-date and even mislaid (especially in the process of digitising all older drawings). Some pipelines may have been altered during close-by construction and never officially recorded. Some pipes and manholes can be heavily covered by vegetation which makes the location more complex than pipelines following a road or pathway. Therefore, located the manholes required to access the lines that have been deemed to require a survey may involve a large amount of time, resources, and in some cases, the wrong sewer could be surveyed. Read and Vickridge (1997) discuss the use of ground probing radars to locate buried pipes, which can reduce the time taken trying to find buried manholes. From industrial practise, it seems common that technicians will trace the pipes back to the closest manhole they can find and work outwardly from there, which may take slightly more time, but requires minimal equipment and less training.

There is also the method of naming sewer lines and manholes to record their location (of which a whole research paper could be dedicated). Naming convention commonly changes depending on county and governing water utility and can therefore cause some confusion. Simply put, it could be beneficial for the water industry to have a standardised method of naming manholes and sewer systems. This could have a multitude of benefits including: less confusion at border locations, accountability for technicians naming newly constructed/found manholes and sewers, straighter forward GIS (geographic information system) use and creation of a universal language which can be used for data software, complying with Synder (2017) who discusses the need for standardised naming conventions. There are many options for naming themes including: geographically, main line or branch line etc. but if there is no naming method, data can be lost, and data errors can damage any information recorded. One of the most crucial aspects to a naming convention could be building the future into it, an ability to grow the network as the areas expand or the networks are replaced. Being able to update the location and name of sewers and manholes onto GIS to then be accessed by others could save a lot of time and money for companies in the long-term.

Once the sewer line has been found and the ID name has been allocated, a survey can begin. Over 95% of all pipes in the UK in 1997 are non-man entry, therefore they rely on alternative methods of inspection (Read & Vickridge, 1997). Consequentially, CCTV within wastewater and water networks are commonplace and are completed by using a camera attached to a rig which is led through the pipe. It is designed to then pan and tilt (manoeuvre to get a closer image) at defects which require further investigation. It is then required for a technician to attach defects to the pipe and grades will automatically be given to those defects based on size. The defects and their grades are governed by the most up-to-date WRC standards which are connected to BS EN 13508-2:2003+A1 (2011) which goes into detail as to what constitutes each of the defect options. WRC have recently released their 5th Edition which includes the movement towards more digital forms of data storage and thus reflects the reduction of physical tapes in favour of cloud based digital records.

Naturally, there are some clear limitations to CCTV surveying, which can be categorized into technician/human based errors and equipment errors. Human errors usually consist of reduced vigilance of the technician, wrongful input of data, neglecting to input data, lack of knowledge of the current WRC standards, poor planning and not using the pan and tilt requirement at defects and connections. Equipment errors include: inadequate lighting, travelling too fast, high water level and therefore missing defects and lack of traction resulting in an abandoned survey (Mitchell, Industrial experience, 2017-2018). All these factors contribute to the final data, therefore the decision making that proceeds this process is greatly affected. By ensuring the output of the final procedure is accurate and complete, it helps the next stages to be of higher quality.

Primarily, the lack of consistent data input from surveys can cause major delays to producing repair designs due to the engineers and technicians having to rearrange the data and put it into a format which is most effective. However, with training on the guidance and standards provided by WRC, it would be possible for technicians to input data in a way which would cut down the data cleaning time. There are alternatives to the standard CCTV which have their own limitations which could reduce the problems. However, due to CCTV being the most common form of surveying sewer and water networks, little is mentioned regarding alternatives within British Standards (British Standard Institute, 2017), and therefore manufacturer's information would have to suffice and be checked in accordance with the Standards. Electro Scan is another way of inspecting the sewer networks, although it is mostly used to check for severe infiltration issues, and therefore may be a more specific piece of equipment used for niche situations, rather than general surveying. WRC (Water Research Centre) discusses this process, stating that the electro scanner was used for a sewer line to access and identify cracks and poorly connected joints. It allowed them to locate defects along the line, which CCTV was unable to complete (WRC, 2019).

There are other options which also use a range of parts from different surveying methods to build a hybrid. SewerVue (2015) discuss a multi-sensor robotic condition assessment tool which utilises LiDAR, sonar, CCTV and penetrating radar (PPR) to get a wide range of data from the pipe to ensure the best decisions on repair are made. PPR can see past the pipe which can help to locate the causes of any defects, assisting to correct them before they damage further pipes or repair efforts. LiDAR projects a laser to create a 3D model of the pipe, showing all faults however minor. Sonar, alongside the LiDAR imagine creates a 360° image of the pipe and its surroundings. Those technologies, together with CCTV gives the engineer a huge amount of information about the pipe and its defects, to help make the best decision regarding repairs. LiDAR is also beginning to be used for manhole surveys by companies such as WinCan, showing a movement towards more data driven analysis. Alongside scanning the pipe, some larger main sewer pipes are also accessible by manual entry by trained technicians who can do a man-entry situation and inspect the pipe in person, however, British pipes rarely get big enough for man-entry inspections.

The main disadvantage to alternative methods than CCTV surveying, is likely to be cost. It is very reasonable to survey a pipe using CCTV, due to it being such a common practise, all main rehab contractors will CCTV the pipe multiple times over the course of repairs being done (Read & Vickridge, 1997). Whereas the Electro Scanning method and Multi-Sensor Pipe Inspection are likely to not be used for every pipe and therefore would usually bring in a specific contractor to carry out those specialist surveys. Exact costs of the Multi-Sensor Inspection tool aren't readily available without a specific project in mind, however, it has been classed as a 'painstaking and expensive experience' by Ravi Kaleyatodi when discussing the use of the equipment for surveying of his local area (Admin from Trenchless Technology, 2009). However, Mr Kaleyatodi continues by stating that the technology is allowing them to predict the behaviour of the pipe and surrounding area, allowing them to focus on cheaper maintenance such as jetting, rather than expensive repairs.

In conclusion, the main aim of a survey is to gather pipe data to build a picture of the pipe and whether it requires repairing, maintenance or further investigation. Therefore, any inspection tool which helps to give more and higher quality data to the technician is beneficial. Within CCTV processes, a standardised system in terms of equipment requirements could prove the key to giving consistent data. This would include, lighting, speed, preparation of the pipe to minimise traction failure and assessments of the water level. In terms of new technology coming through and being more available to the industry, it would be prudent to create a standard for use of those processes, to once again provide consistency and give accountability to technicians. Although it hasn't been discussed in detail in this section, ways of compiling and merging data together to give a holistic view of the pipe and its surroundings could also be utilised in the surveying aspect of the rehabilitation process. Combining the information provided within the prioritisation stage and the surveying stage, can help to build up a picture of the pipe and help the industry be at the forefront of pipe behaviours, allowing them to begin to see patterns of behaviour which lead to defects and help solve the issues before the cause defects.

Therefore, it is the recommendation of this paper that a large-scale database be formed, which can accommodate surveying information as well as the information earlier discussed regarding internal and external pipe characteristic information. Alongside the database, there is a void growing regarding standardised information for alternative methods of inspection which could be solved with the creation of British, European or International Standards to address the use of Electro Scan devices etc. Finally, companies who conduct pipe inspections are required to train staff to the most up to date information and WRC standards, proper training could help save time and money in the long term.

Repair allocation

As earlier established, there are many ways to survey sewer networks. There are also several different repair methods that are available, primarily the options are: CIPP liners; patch repairs; pipe bursting and open cut / excavation style replacements.

There are many economic and environmental consequences to either method and the requirements for choosing one of the methods as opposed to a different one may include: access, defect severity, location, diameter, etc. It can therefore be difficult to establish which repair should be allocated to a case without individual assessment which can be time consuming.

Although there are many different British and International Standards which discuss the testing, installation and properties of CIPP lining, there appears to be a gap in the guidance regarding which repair should be allocated for each type of defect.

Within industry it is common to have ‘rule of thumb’ which leads towards a specific repair method depending on the length, how many defects are present and the severity of the defects. Once an initial design has been recommended using that method, a more in-depth check will be complete, especially when large numbers of patches, long lengths of CIPP liner or open cut excavation are being recommended. However, it is difficult to trace back the ‘rule of thumb’ method to any scientific or engineering based argument. In the case of industry experience, it seems to have come from a water utilities company who put a rule in place to monitor costs. These ‘rules of thumb’ have the ability of being potentially bias towards money saving in the short-term, as opposed to the holistic long-term approach recommended by Steffens (2018). To carry the idea of long-term strategy and holistically viewing the sewer network, it could be prudent to have specific methods for assessing the required repairs for each pipe.

As previously mentioned, there seems to be a lack of guideline within the Standards as to an engineered algorithm for assessing repair appropriateness depending on different factors. Usually, in industry, the decision-making process is led by cost/benefit analyses, as well as considering disruption and environmental impacts, which tends to lead contractors and designers back towards trenchless technologies (Hinte, 1994). However, it is still unclear as to whether trenchless repairs are being used when truly appropriate for the defects present.

The WRC provide a standard which is closely linked to BS EN 13508-2:2003+A1:2011 to standardise the coding process of defective sewer lines. Throughout those standards, there fails to be guidelines to link the defects to associated repair options. The general process for allocated repairs in accordance with the defective status of the sewer pipe follows the basic method of finding the problem, commonly using CCTV or other inspection tools, assessing the risk, economics of the repair, local impact and the impact of doing nothing, discussing different repair methods, completing a cost-benefit analysis of the problem and allocating the cheapest repair option which rectifies the problem.

This examination is mostly looking into the effect of CIPP lining and the process surrounding CIPP lining. However, for completeness a wider view into alternatives will be briefly discussed. Stabilization, which requires excavating the pipe and restabilising the outer soil surrounding the pipe, this is not particularly common due to the lack of necessity and associated costs. Localised repairs, which can be small sections (usually 1-2m long) of CIPP liner which is used to patch a small specific area of the pipe. Full line renovation of the pipe which lines a section between two manhole entries, this can be completed using the CIPP lining process or slip lining which requires a larger trench to pull a pipe into the existing pipe.

In summary, there is a distinct lack of guidance provided as to how to progress from the defect collection phase at the surveying stage onto initially designing repairs. Possible solutions could be a standardised algorithm that considers key factors of the pipe and the defect grades attached using the current WRCSS codes. In the meantime, it could be possible to create a simplified flow chart style guide to provide a higher level of standardisation for companies and water utilities as to how to proceed with repairs. This could remove the potential risk associated with ‘rule of thumb’ methods and lead onto a tested and safe process. Companies such as WinCan are already trying to provide such software in part, therefore the future is likely to include more automated decision making.

Installation
When looking at the installation process of CIPP liners, there is a broad range of details which must be accessed, situations often materialise on site which couldn’t have been foreseen forcing decisions to be made and decisions made on the day. These circumstances can consist of: high water levels; difficulties with access; traffic and changes to the site between the planning and installation dates. Each manufacturer is likely to have slightly different installation requirements, but the general ruling can be found in WIS 4-34-04 (1995). However, the guidelines given by WIS 4-34-04 (1995) seem to only guide the technician back to the supplier’s guidance and fail to give general information regarding preparation requirements, equipment needed, curing options or transportation of the liner.

Peregrine (2007) also discusses the impact of the manufacturing decisions in terms of the amount of catalyst and accelerator added to the resin to control the speed of the chemical reactions of the cure. Any manufacturer can promise that a liner will perform to a certain level, however, if the product isn’t installed to the correct standard the attributes are unlikely to be met. Changing the ratio of catalyst to accelerator, even slightly has enormous effects on the properties of the liner, therefore, it would be preferable for the installation to be made in a controlled environment, where the consequences are monitored. Peregrine (2007) also highlights the need for accountability throughout, especially for installation technicians to ensure best practise.

There seems to be a considerable lack of standardised installation guidance for technicians. It’s difficult to see if all manufacturers follow a standard procedure or if they differ dramatically from company to company. Therefore, there could be a need for a clearer set of standards to combine various manufacturers with British / European / International standards to ensure all installations are following the same process. Thus, safeguarding the process and creating a blueprint for ‘gold standard’ installation which can guarantee CIPP liner performance. This ‘blueprint’ could also include guidance on procedures to ensure a safe and effective installation when weather, traffic, access etc. causes delays and/or alterations to the installation process. Thus, moving towards consistent installation regardless of the situation.

However, as discussed in previous sections, a key recommendation for the installation process would be creating a way to keep accountability of technicians and record the decisions made. This links to the discussion discussed for other parts of the process that a process of collecting and visualising data from sewer line interactions could prove to assist many of the issue’s contractors are currently having to deal with.

Post-installation, some liners are required to be tested. This usually takes places directly after installation has been completed.

Maintenance
Once the CIPP liner has been installed there are various things which can limit its effectiveness without causing severe or collapsing failures. Commonly, silt build up and/or roots can cause defects which build up to ULS failures requiring additional rehabilitation. Alongside the gradual built up of external factors there is also the

consideration of the pre-existing defects which caused the original defects to required repairing. For example, a pipe which has been highly deformed due to external pressure build-up or root expansion, will still be under pressure from the roots unless the external factors have been removed. Therefore, the original defects may continue over time, to damage the liner, therefore this issue requires close monitoring. By increasing the quality and accessibility to data, all information regarding the defects, installation evidence and previous survey dates pipes which are susceptible to silt build up or other long-term defect causing issues would be accessible and easy to identify.

Ridgers, Rold and Stål (2012) discuss the impact of continued contact between sewer pipes and growing roots, they discuss that although there is a low level of modern pipes impacted, older pipes continue to be heavily damaged. This appears to be due to a lack of sharing information regarding new and developing plans, resulting in new trees and plants being installed over a sewer line which could be cause larger faults resulting in expensive repairs being required. Because of the lack of space for plants and trees to grow into due to paving and road infrastructure, the roots spread to where they can expand and gain nutrients which leads them to the sewer pipes and sees their growth rapidly increase (Ridgers *et al.*, 2012). Ridgers *et al.* (2012) also discuss possible adaptations to pipes to enable them to be more protected from root infiltration by sealing the joints, which are the most vulnerable place for roots to occur. This may not seem like standard maintenance practise but by considering the location of the sewer pipes and rearranging new planting sites accordingly, the likelihood of further rehabilitation being required can be greatly reduced and with it the cost impact.

It should also be considered as routine maintenance to protect the sewer by regularly jetting to remove debris and silt which build up over time, damaging the flow capacity of the pipe and can have the potential to increase the likelihood of more severe defects forming which will affect the structural integrity of the pipe (Read & Vickridge, 1997).

Maintenance proves to be of continued importance (Karoui *et al.*, 2018), it is common for large cracks and holes to occur in pipes once a small defect has started. However, if the pipe is held in optimum state, and considerations are made to ensure its upkeep then it is reasonable to assume that defects will occur less frequently, although there is a chance for further testing here to establish the cost benefit in the long-term. CIPP liners are still subjected to the same external factors as the original pipe and therefore could potential become defective. Therefore, maintenance should still be continued for a lined pipe, which can help to reduce likelihood of further rehabilitation being required.

The creation of a best practise database including all interactions with a sewer line to be recorded in a life cycle style database, showing all surveys, all repairs and replacements, as well as pipe and external information could help increase knowledge to best care for the pipe, enabling the best use of resources to be aligned with the pipes, ensure that future-plans are made with the sewer line information considered and warrant that they are maintained at an effective level, reducing long term replacement costs. There is also a possibility for future research focusing on the full benefits of continued maintained of a sewer line compared to a pipe that has been left without regular upkeep. This could help the industry see the benefits of long-term maintenance to reduce future rehabilitation costs.

End of life

Little is known regarding what happens to a CIPP liner due to the method being relatively young compared to its tested life span of 50 years (BS EN 752:2017, 2017 & Alam *et al.*, 2015). However, some CIPP liners have had to be removed because of failing either due to poor installation or large defects. Questions naturally arise about what happens to a CIPP liner once it has become obsolete, whether it be recycled or reused. Some plastics can be melted down and reused, dependent on their curing method, the same might be possible for CIPP liners.

Picote (drain cleaning and drilling company) have a CIPP removal device, however it can only be used to remove CIPP liners installed in cast iron or clay pipes and removes the liner by slowly grinding it down, completely removing any chance of reuse. There are commonly more and more PvC pipes present, which would require a different method. Another method is blasting the liner with a high-pressure jet washer and then using a robotic cutting to break the liner down further to be removed at a manhole access point. This looks to be the 'less technical' option, however it would be effective with all types of pipes and diameters. However, it is possible that small particles of the CIPP liner won't be picked up at the manhole access and would then be added to the water stream, causing environmental issues further down the process.

There is clearly a distinct lacking in guidance from the British Standards as to how to a standard approach to remove CIPP lining, which could be very beneficial as we come closer to the older CIPP liners approaching their design life of 50 years.

Testing

Please note that for the purposes of completeness, the testing stage of the 7-step process would usually be completed directly after installation. IKT (Institute for Underground Infrastructure, Germany) release a liner report annually which shows the number of companies who have submitted liners to be tested for: water tightness, wall thickness, flexural strength and Young's Modulus. Within the 2003/2004 Liner Report, there were 9 companies who submitted samples, none of which passed all four tests (IKT, 2004). The Liner Report has grown significantly since the first report in 2004 to now include 32 companies, 9 of which achieved 100% pass rates across all four tests. As highlighted within the study performed by IKT (2017), the number of samples which passed all tests has varied over the last 5 years, not reaching above 68% since 2012. Orman (2016) commented on the importance of having regular testing for rehabilitation to build confidence in the industry and ensure consistent performance.

Owing to CIPP lining being relatively young, established in 1971 (Berglund *et al.*, 2018), there aren't many test samples old enough to test the full extent of its life span. BS EN ISO 112964-4:2018 (2018) states that CIPP liners should have a life span of 50 years. BS EN 752:2017 (2017) discusses the importance and impact the design life has on all aspects of the sewer but doesn't give any further guidance as to how long that should be. This could allow for industry-wide acceptance, instead of focusing on the possibilities of extending the life span of repair materials to increase sustainability.

Due to the youth of the technique it is hard to imagine how the life span of 50 years has been thoroughly tested to give a high level of confidence. Alam *et al.* (2015) attempted to tackle this issue by testing 18 CIPP samples ranging from 5-34 years old. The overall observations show that the CIPP lining samples examined were performing well and only 1 was failing, in terms of flexural strength. The life span of 50 years Alam *et al.* (2015) agree is realistic, as does Allouche *et al.* (2014). Importantly, Alam *et al.* (2015) raise the point that sewers with CIPP lining being installed had enough structural defects present to warrant a liner being fitted, therefore unless the original issues have been treated, defects could continue to form and damage the liner.

Commonly, testing samples will be collected immediately after installation. They are usually taken from the end manholes or interim manhole. Manhole cuttings would be required regardless of testing obligations, therefore testing can reduce waste. It is usually at the discretion of the client as to the frequency of testing, some require every liner to be tested whereas others require a test every 1000m of CIPP installed.

For the basis of this research, 4 different CIPP liner samples were provided. They covered a range of different sizes and thicknesses which can be seen in table 1. This investigation has chosen to focus on 3 main testing elements which are aimed to provide a range of values and give a holistic view into the characteristics of the CIPP liner samples, wall thickness, flexural strength and electron microscopy imaging. A more detailed characteristic table can be found in appendix 1. As previously mentioned, the 3 key sections; thickness testing, flexural strength testing and electron microscopy imaging will have each have a methodology, results and discussion section. This is to focus on the key points of each element before bringing the results together for a more holistic view of the testing stage of the research.

Figures 1 and 2 show the standard shape of the samples, specifically batch C.

Table 1: Sample characteristic overview

Sample Batch	Number of samples	Average Size (mm)	Average Thickness (e_m) (mm)
A	8	50 x 100	4.4
B	8	50 x 100	4.5
C	6	50 x 200	6.1
D	4	50 x 150	5.5

Figure 1: Batch C samples longitudinal view.

Figure 2: Batch C samples prior to testing. Plan

Please note: all experiments were conducted under the standards of atmospheric conditions required for testing and storage of the samples are in line with guidance from ISO 291:2008. All samples were cut in accordance with ISO 178:2010+A1:2013, resulting in 26 samples, sizes and thicknesses are detailed in appendix 1.The standards for the required values for each test are in BS EN ISO 11296-4:2009 and are recorded in table 2.

Table 2: Standard Mechanical Characteristics of Pipes (BS EN ISO 11296-1:2009)

Characteristic	Requirement
Short-term flexural modulus, E_o	Declared value but not less than 1 500 MPa
Flexural stress at first break, σfb	Declared value but not less than 25 MPa
Flexural strain at first break, ε fb	Declared value but not less than 0,75 %

Thickness Testing

In line with IKT testing regimes, the thickness of the CIPP liner has direct bearing on its ability to perform in line with expectation.

Methodology

Thickness testing was completed using a high accuracy digital Vernier. ISO 178:2010+A1:2013 recommends taking numerous readings for each sample sheet and taking an average, taking a minimum of 6-point thicknesses around the perimeter of any given sample.

1) For each sample sheet a thickness reading using the Vernier was taken at 2.5cm intervals around the outer edges of the sample.
   a. An accuracy of 2d.p. was kept during the testing.
2) A mean average calculation was completed, resulting in an average thickness for each sheet.

N.B. The average thickness for each sample sheet was used when calculating the size of the flexural strength test samples.

Results

Table 3: Thickness Testing Results

Sheet Sample ID	Total Thicknesses (mm)	Number of readings	Average Thickness	Range (mm)	80% of average (mm)
A	70.75	16	4.4	2.47	3.52
B	90.08	22	4.5	2.53	3.6
C	148.03	23	6.4	1.87	4.88
D	99.06	18	5.5	1.8	4.4

Table 4: Thickness Testing Range Results

Sheet Sample ID	Average Thickness	Range (mm)	Lowest Value (mm)	80% of Average (mm)
A	4.4	2.47	3.64	3.52
B	4.5	2.53	4.02	3.6
C	6.4	1.87	5.4	4.88
D	5.5	1.8	4.54	4.4

Table 3 shows the total thicknesses recorded (the sum of all thicknesses measured around the perimeter of the sample) and the number of readings to calculate a mean average thickness of each sample sheet. Table 4 shows the details of the range of results present in the values.

Discussion

The thickness testing proved to be more complex than initially thought, mainly due to the high level of variance throughout all the sample pieces. The samples aren't even, some are very jagged which causes concern and confusion about where the best location would be for the truest value of the thickness. Therefore, the decision was made to increase the minimum number of readings from 6 per sample, to taking 1 reading every 2.5cm around the edge then taking an average. However, as shown in table 4, the range was sometime as high as 58% of the average thickness (in the case of sample sheet B), which reduces confidence in the average being used.

Although there was no design thickness provided from the liner supplier, it would be logical to assume that a roughly uniform thickness would be preferable. It would enable the curing process to be equal throughout the liner and would reduce areas of weakness which could be susceptible to defects and failure in the future. BS EN ISO 11296-4 (2018) state that the minimum requirement of wall thickness is 80% of the design thickness (see table 3). However, regardless of the large ranges present throughout all 4 samples, each of them would pass the test if their average thickness was the design required thickness.

Overall, this test has shown that the minimum thickness isn't below 80% of the average but the range of values could create cause for concern in an on-site practical situation. Thinner parts of the liner could be more vulnerable to defects and increase the likelihood of a failure occurring, resulting in removal of the liner and reassessing the pipe, which can be very costly and time consuming. Potential recommendations could encourage a higher level of care when prefabricating the liner and ensuring the fibres are evenly spread, as well ensuring the liner is fully inflated before curing.

Flexural Strength Testing

Flexural testing is a crucial aspect of this paper's testing, it will enable the calculation of a Young's Modulus, as well as looking at the level of displacement and the failure behaviours of CIPP liners. As a hypothesis it would be thought that although there will be ranges of results throughout the samples the general relationships will follow a similar pattern throughout different the batches.

Methodology

Following samples being cut using the method discussed in ISO 178:2010+A1:2013 26 samples were created for flexural testing, shown in figures 3 and 4.

Table 5: Sample batches and associated testing spans.

Sample Batch	Number of samples	Average Size (mm)	Average Thickness (e_m) (mm)	Span (mm)
A	8	50 x 100	4.4	60
B	8	50 x 100	4.5	60
C	6	50 x 200	6.1	120
D	4	50 x 150	5.5	80

1) The 3-point bending test machine was calibrated, and a span set based on the length of the sample. Sample span can be found in table 5.
2) Samples can be inputted into the machine, as shown in figures 3 and 4.
3) The applied force load cell was lowered to sit on the sample.
4) A load of 10mm/min was set, following guidance from ISO 178:2010+A1:2013.
5) All appropriate data regarding the sample sizes etc., was inputted into the testing machine.
6) The machine was the balanced, calibrated to 0 throughout.
7) Load was applied at the set load, strain (%) and displacement (mm) were recorded and a Young's Modulus was calculated.

Results

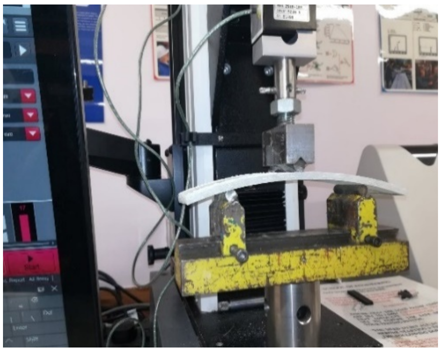


Figure 3: Flexural strength, 3-point bending test set-up.

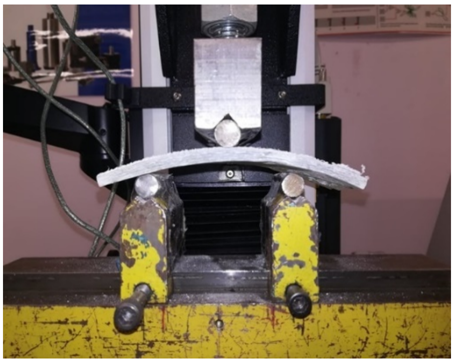


Figure 4: Flexural strength, 3-point bending test set-up.

Table 6 shows the range of calculated Young's Modulus results calculated by the 3-point bending testing machine, and their associated ranges.

Table 6: Summary of Young's Modulus Results per Batch

Batch	Average Young's Modulus (MPa)	Range (MPa)
A	2238.45	1954.2
B	1869.77	1962.7
C	2628.72	555.0
D	2745.53	361.5

Figure 5 shows the frequency of Young's Modulus values across all samples. Full batch breakdowns of the Young's Modulus can be found in appendix 2.

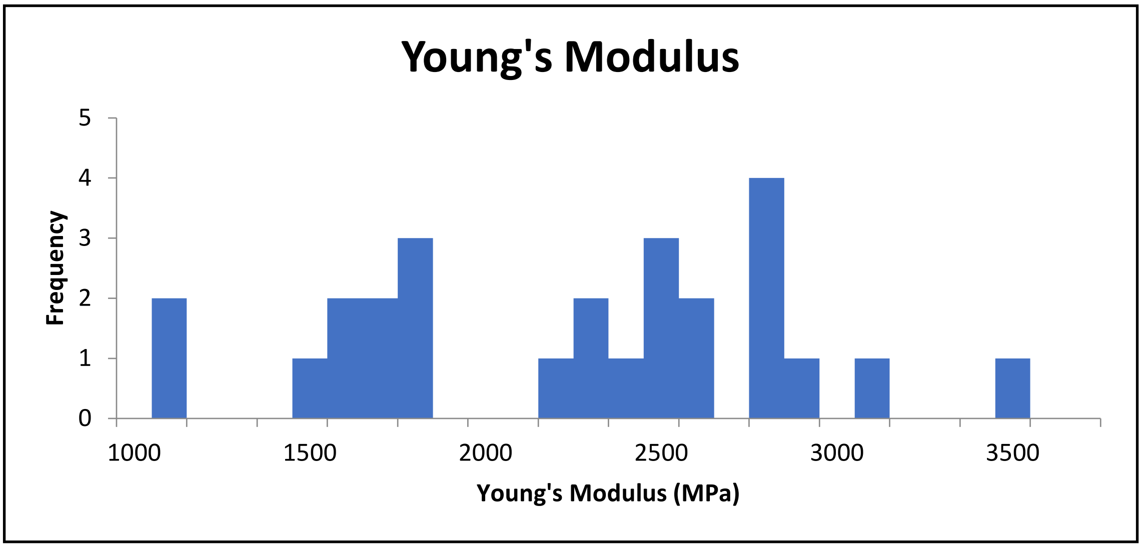


Figure 5: Young's Modulus Histogram

Figure 6 shows a range of 2 samples from each batch of testing completed and the associated displacement displayed. This has been created to quickly compare different batches of testing without cluttering the graph. Full graphs for each batch can be found in appendix 3.

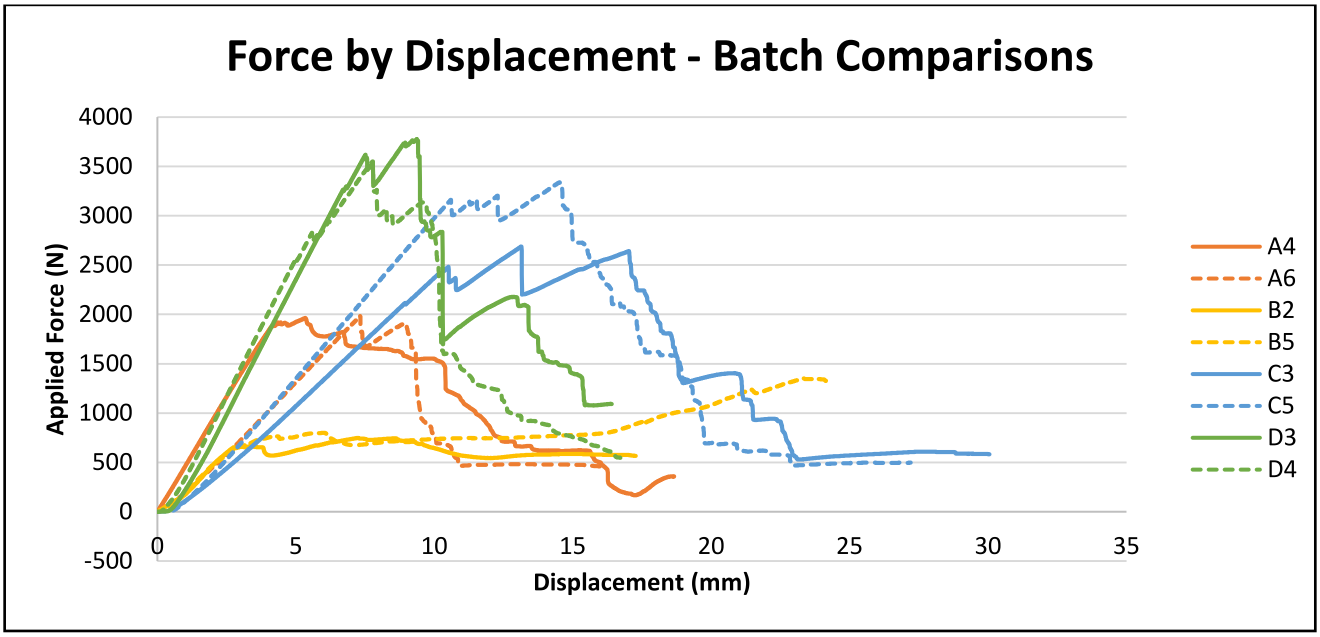


Figure 6: Force by displacement - batch comparison

Figure 7 is showing the same style of batch comparison but comparing the applied force with the flexural strain (%). Full batch graphs can be found in appendix 4.

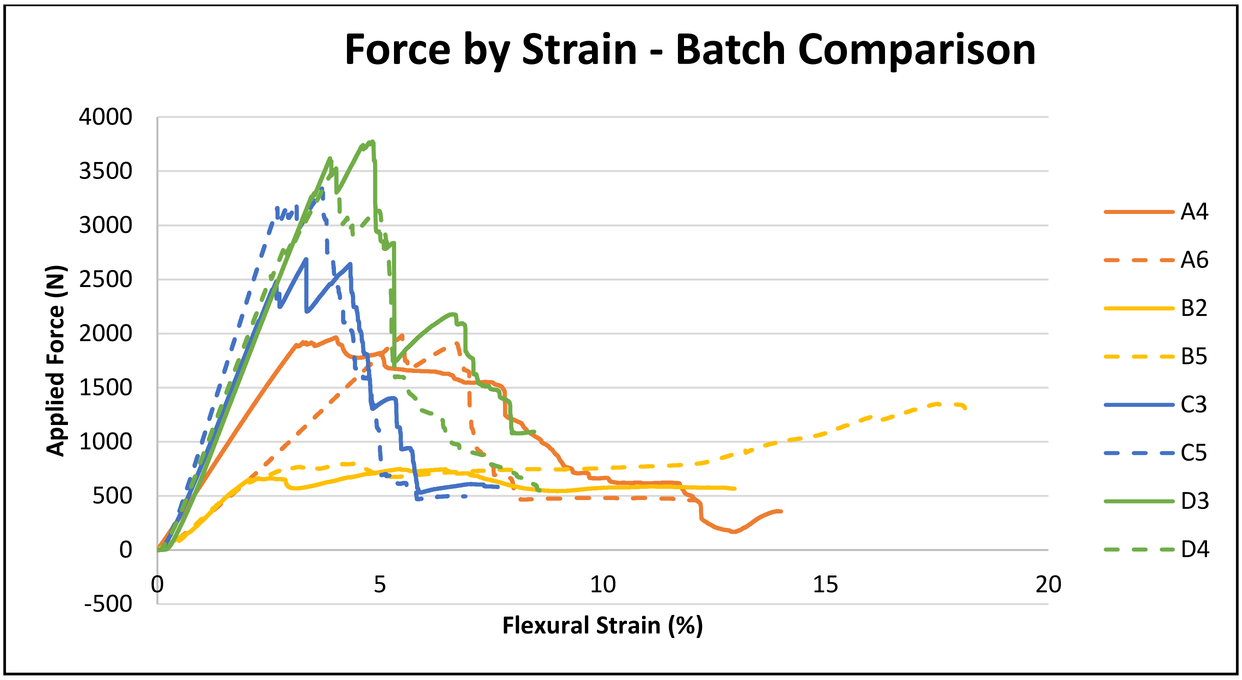


Figure 7: Force by strain - batch comparison

Discussion

The flexural testing was established as one of the main objectives of this investigation, to see the strength associated with CIPP lining and how the CIPP behaved when failing.

It is worth noting that a mistake was made when calculating the size of the required samples based on their thicknesses, however, this hasn't impacted the calculation of the Young's Modulus as the equation used within the equipment considers the width of the sample, counteracting the impact of the error.

The Young's Modulus is directly dependent on thickness and as such it would be expected to have a range of values based on the high range of thicknesses present in the samples. Based on guidance provided in BS EN ISO 112964-4 (2018) the minimum Young's Modulus required for CIPP liner is 1500 MPa. This has been met by all sample averages and therefore based on the average no sample would fail on that count. However, samples B1 and B4 provided a Young's Modulus of 1183 MPa and 1184 MPa respectively which would fail the standard flexural strength test. On the other hand, batches C and D recorded an average of 2623 MPa and 2745 MPa respectively which could be deemed an overdesign. Although, little is known about the specific site requirements for these CIPP liners and therefore they might have required a higher strength for a site-specific issue.

Figure 6 shows a range of different samples, looking at the applied force against displacement, it has been created to give a quick comparison between 8 different samples across 4 different batches, please see appendix 3 for individual batch graphs.

Batch B is considerably different in behaviour than the 3 other batches, having a much lower maximum applied force. When being tested, batch B behaved differently in failure also, failing with high ductility and almost no external delamination present on many of the samples' surfaces, as shown in figure 9. This caused a slight change in the properties of the test, as the edges of the point load applicator (shown in a red circle in figure 9) were touching the sample, changing the loading from a single point load to a 3-point load acting more in a uniformly distributed load format. The lack of delamination and the elastic behaviour could show that the sample hasn't been fully cured compared to the other samples. After the testing of batch B, the samples returned almost to their original shape.

As shown in figure 8, the expected form of failure would be delamination, which cause vulnerable areas more susceptible to other defects. The 3 batches (A, C & D) all failed with delamination as their clear behaviour showing similar graph shapes, even though their first break point is varying, they show a very clear first break point and deflection

Figure 8: Batch A testing behaviour.

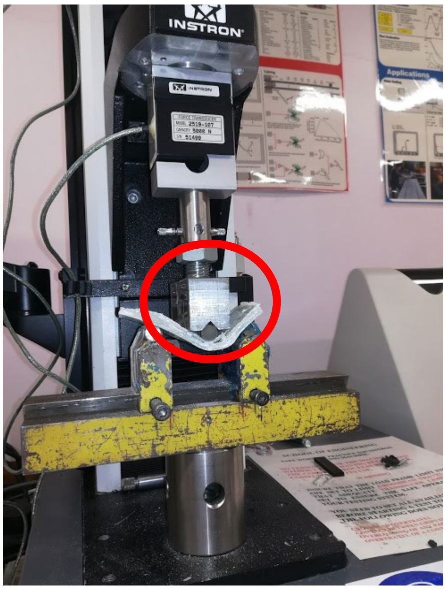


Figure 9: Batch B testing behaviour.

model which would be expected in a composite matrix, carrier material (shown in figure 6). Whereas it is difficult to see the actual failure point of batch B due to the ductility of the failure (see figure 6 and appendix figure 3B). The maximum displacement also ranged dramatically throughout the varying samples, appearing to level out at roughly 12, 20, 25 and 16mm for batches A, B, C and D respectively. Which shows a considerable range, once again batch B showed variation from the other samples and even at 20mm deflection the sample hadn't reached its maximum, showing it could potentially keep deflecting under heavier loading.

Overall, the values of displacement and maximum applied force have a large range different between batches, although that's to be expected as the thicknesses of the samples vary. However, it would be usual to expect a similar result throughout the samples which have been cut from the same batch sheet. Within the varying batches there are differences within the samples, specifically, A7 and B8 show differences from the trend of their batch, with a difference in maximum load by 500 and 1000 MPa respectively. Showing that even within the same batch the samples behave differently, this could be contributed to the range of thicknesses within a batch.

The applied force and strain relationship (as shown in figure 7) follows like the deflection graphs, each batch following the same rough relationship with few exceptions. The highest strain was present in batch B, which following earlier discussion, regarding the high displacement present, is unsurprising.

Batch C seemed to be the most consistent of the batches, (shown in appendix 3 and 4, in figures 3C and 4C respectively). Batch C also has one of the lowest ranges of Young's Modulus compared to the other batches. This could show that the installation methods were most consistent within batch C compared to other batches.

Some issues with the testing are potential inconsistencies from the desired size/thickness sample required by ISO 178:2010+A1:2013. As well as the sample sliding along the supports during testing, due to high ductility, which can be shown in figure 9. This created a different effective span and different testing parameters that wouldn't have been considered within ISO 178:2010+A1 (2013) guidelines.

In conclusion, a more uniform spread of results and similar failure behaviour was expected throughout the samples with small variations between different batches that have different thicknesses. As discussed, this hasn't been the outcome of the testing, there were much higher levels of variance between samples and batches under all aspects of the testing. Overall, 92% of the samples has a Young's Modulus of higher than 1500 MPa which is higher than the rate IKT published in their 2017 Liner Report (IKT, 2017). However, this is a much smaller quantity of samples and therefore is not as reliable as the 2,152 samples tested under the 2017 Report. The level of displacement and strain has less of a clear failure criterion, however, batch B behaved differently to the other samples with the level of ductility and lack of delamination.

This deviation from the hypothesis could be attributed to external factors having a higher level of effect on the characteristics of the liner than previously thought. However, it's more likely to be due to several small decisions made throughout the process of installation.

Electron Microscopy Imagine

This testing will be used to assess the mix of resin and fibres present in samples and potentially link the spread of fibres and resin to the failure behaviour and other results.

Methodology

1) The samples were cut to a specific 10mm strip from the existing samples testing for flexural strength.
2) These samples were then loaded into the sample case for the Jeol JSM-6610LV machine.
3) The machine was then calibrated to scan electrons over the surface of the sample to create a magnified complex image of the sample.

A sample of images created using the EM method can be found in figures 10 – 13.

It was also possible to check a composition of one of the samples, 4 points were identified and then a composition was created based on the elements present for each of those points. The results can be seen in appendix 6.

Results

Please note the red circled areas represent the edge of the samples and will be used to identify discussions surrounding the spread of fibres throughout the samples. Whereas: The white areas represent glass reinforced carbon fibres, and black a carbon-based resin. A composition breakdown of the samples is included in appendix 6, indicating the elements present in the sample. This showed that the resin comprised of mostly carbon, and the fibres are silicon and oxygen, commonly known as glass reinforced fibres, a standard fibre type for composite materials.

Discussion

As shown by the red circles on figures 10-13, the spread of fibres and resin is different throughout the samples. The overall photos were the main point of interest for this research, however more detailed photographs are available in appendix 5. These images show the detail of the fibres across the sample, confirming that all samples have a larger number of fibres in the centre than at the edge, which would be expected.

Figure 10, representing a sample taken from batch A shows a distinct lack of fibres at the edges of the sample which could contribute to the brittle nature of the failure observed during testing. However, figure 12 and 13, show a more varied spread of fibres and they also exhibited a brittle delaminating form of failure.

Figure 11, representing batch B, showed an overall good coverage of fibres throughout the width of the sample with a lack of voids present (large black areas without fibres). The connection with the fibre spread and form of failure could be studied further to investigate the connections through a larger number of samples. Figure 9 showed

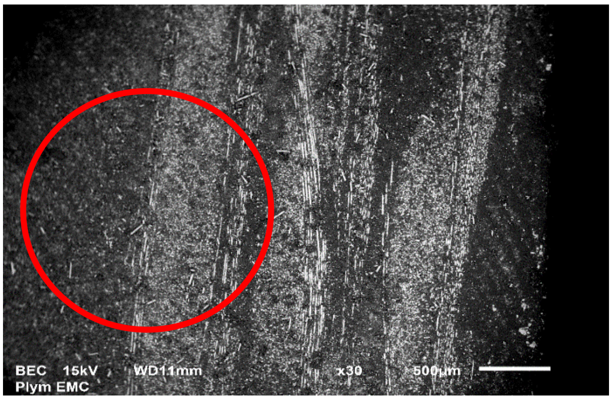
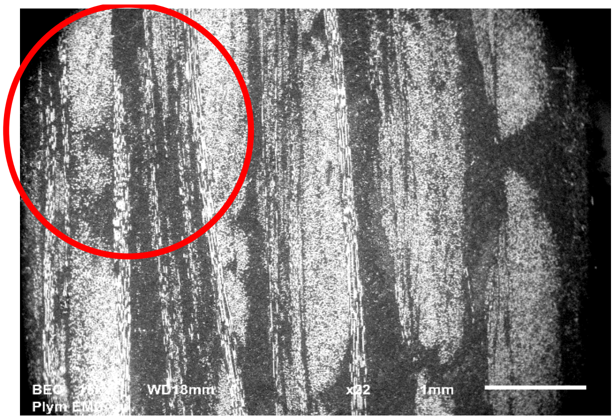


Figure 10 & 11: Sample A - whole thickness (L), Sample B – whole thickness (R)



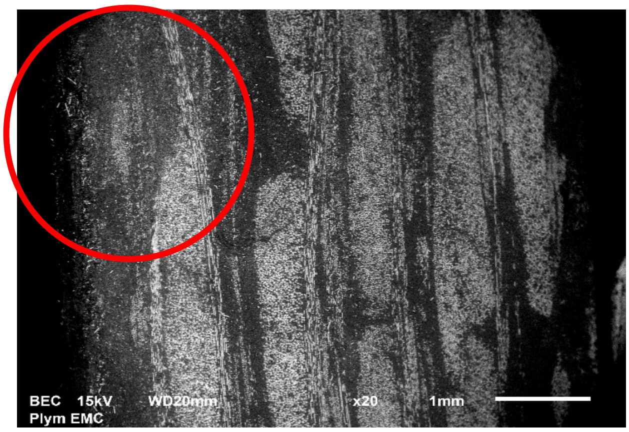


Figure 12 & 13: Sample C - whole thickness (L), Sample D – whole thickness (R)

some voids present throughout sample C, but overall the sample indicated a good spread of fibres, reaching to the edges of the sample. Sample D, shown in figure 13 shows less fibres than sample B and C at the edge of the sample and some larger voids. However, this seemed to have little impact on the failure method of the sample, as it failed the same as sample A and C.

It would be expected, that there would be a higher level of consistency through the samples as they are installed and pre-fabricated in the same way. However, there were evident differences between all samples. This style of pre-fabrication should be able to create a factory safe liner which would be expected to be more consistent. However, installation practises have an impact on the composition of the liner, which seems to be a growing theme within the testing conclusions. There could be a way to standardise the process of fabrication and installation, however, it is unlikely that any standardised process will be able to mitigate away from on-site situations which dictate the installation process.

The composition shows the carbon-based resin and glass reinforced carbon fibres, both of which are expected and common for this form of construction material.

Potential other testing

There were other tests that could have been possible if resources and time were expanded, including long-term creep tendency, which would investigate the longer-term consequences. It would be preferable to compare between standard modern PVC pipes and lining to see the difference to the long-term durability of sewer pipes.

IKT complete a water tightness test using the electron microscopy equipment, however for this paper it was outside the realm of knowledge and resources. It would be beneficial to compare different sample thickness and curing methods to see how water tightness is affected by different components, as discussed by Peregrine (2007).

In hindsight, it would be useful to access a sample to see if any defects are present, and then complete flexural strength testing to see if there is any correlation with where and how the sample fails. This could assist in updating installation methods to limit defects being creating during the installation.

Testing Conclusion

Bringing together the discussions of each individual testing shows some distinct differences from the expected outcomes. The hypothesis expected for all levels of testing was that the samples may differ slightly but overall, they would follow similar patterns and have similar values for Young’s Modulus. As shown throughout this section, that hasn’t been the reality of the testing. Large ranges were found when comparing batches and even within batch samples.

Possible solutions could include creation of a standardised set of requirements throughout the country based on British Standard guidance, alongside BS EN ISO 112964-4 (2018), that provide guidance as to how to best install and fabricate the liner to produce consistent and successful results. A stricter look into BS will increase the quality assurance, helping to increase the confidence in CIPP technology further and find new uses for this technology.

The other concern which could be considered are the lack of guidance for testing curve samples, the standards assume an even thickness across the samples which has been disproved, showing that the thickness ranges considerably through all samples. This could cause reduced precision considering the BS EN ISO 11296-4:2018 guidance on curved sewer liner sample sizing requiring a thickness accuracy of -+ 1mm.

BS EN ISO 178:2010+A1:2013 suggests testing a minimum of 5 samples, however we only 4 batches. Although, from cutting up our batches, 26 samples were created which could be considered a compromise in sample variation.

There are also new and upcoming materials which could reduce the variation between sample also, namely Fibrwrap have created a similar material. They are currently being used to reinforce concrete and steel in renovation projects for buildings. Although, there is future potential for the material to be made into tubes and used as a high-end reinforced material for CIPP lining, potentially reducing the variation.

Whole Process Discussion

This section will be used to summarise all the stages discussed so far.

The prioritisation of sewer pipes to assess which lines have the highest criticality is the first stage that water utilities companies meet. Getting the prioritisation stage of the method wrong can cause issues further down the process, allowing defects to cause large issues if they are overlooked. A simple MCDM (multi-criteria decision making) tool considering physical and external characteristics appears to be unanimously recommended by other studies. It would consider the pipe data, such as diameter, length, age, material etc. and could be expanded to include external characteristics such as soil type, location, traffic weight etc.

Surveying of the networks relies heavily on accurate information regarding its location and knowledge of the technicians to be able to name and locate sewers which may not be as expected as well as the ability for technicians to be able to update locations quickly on GIS applications while on-site will ensure that information isn't lost.

There are many surveying options for sewer pipes, however the most common remains to be CCTV rigs. These can be successful when used appropriately and the known concerns are mitigated, namely the technician requires appropriate training on current WRCSS standards for knowledge of defect coding, an understanding of how to get the best imagery from the rig, correct lighting and speed etc. For specific site issues there are more complex investigative forms of surveying which can use sonar scanning etc. to create a more holistic view of the sewer and its surroundings. However, these methods are costlier and therefore are usually not used unless there are specific site issues such as heavy infiltration.

Allocation of repair methods links with the prioritisation tools earlier discussed. There are many repair options, from excavation to fully trenchless options which each have advantages and disadvantages economically, environmentally and to the local businesses and residents. By creating an algorithm considering all factors, the engineers can create an automated process which would save time and money, but it would also enable the process to be standardised, repeatable and reviewable. The installation process commonly follows manufacturing specifications. It has been shown that on-site decisions make a considerable different to the liner. Therefore, there is potential for further standardisation or an algorithm to give guidance on actions to take based on situations that materialise on site. This would help increase accountability for the decisions made on site and their possible consequences.

The results of the testing conducted on lining sample showed that each sample, even from the same batch, can produce different results. BS EN ISO 11296-4 (2018) has been used to provide guidance on testing curved samples and given approximate values that the liner should be able to achieve. This showed that the 92% of liner samples pass the flexural strength testing, the wall thickness testing is less clear as design thicknesses haven't been provided. The range in results from sample to sample could be due to the decisions made on-site. Once again, a clearer, more standardised method could solve these inconsistencies and help create reliable liners. Good consistent maintenance can decrease the likelihood of repairs being required. Regularly jetting and surveying the pipes can reduce the likelihood of a defect forming. This is also linked with the prioritisation tool and if the data is correct then it could be possible for the data to create a date for when the pipe will next require maintenance.

At the last stage of the process the liner could potentially be removed or replaced. Little known about the environmental impact of the grinding down process used to remove liners but there are new and upcoming processes which may in the future find a way to remove liners without threatening the environment. Data management is a continual theme throughout all recommendations and conclusions of all the 7 stages which could act as a continuous record for any given pipe, showing its characteristics as well as any interactions that pipe has been subjected to, including surveying, any repair work, maintenance etc. It could also hold all survey CCTV videos which would enable the owner to see the progression of the pipe and any build-up of silt etc to monitor its situation long-term. With the use of a data management tool and a stricter Standard which covers the whole CIPP process, it may be possible to rule out the issues and concerns found during this research.

The future

As time progresses, it is likely that engineers will face further problems, contributing to our changing climate, increases in population and new repair techniques being developed. There is much written about climate change and the effect on the environment in the future, less is known regarding what society is doing to prepare.

Increases in dry weather and sewer overflows which are expected to cause further consequences for treatment works due to high flows (Astarair-Imani *et al.*, 2012). Semadeni-Davies *et al.* (2008) agree that demands put on sewers will rise due to increases to surface runoff and a lack of sustainable urban drainage in place to deal with the surge in urbanisation. Discussions regarding needs for modelling climate change impacts in key areas are commonplace in assisting countries prepare for hotspots of flooding etc. (Langeveld *et al.*, 2013). Computer modelling will allow for further understanding into the potential for longer seasons and more intense climatic storms which will put pressures on combined sewer systems worldwide (Semadeni-Davies *et al.*, 2008), which in some areas are considerably old and struggling.

To battle all the future requirements, perhaps the industry needs to be more open to new and innovative ideas to attempt to achieve the balance of the environment, economy, disruption, maintenance and longevity. Read & Vickridge (1997) discussed as much, over 20 years ago, highlighting that the 'ideal' rehabilitation method would consist of specific points which will contribute to the overall perfectly balanced solution.

As technological advances continue, new materials and new processes continue to develop. Fibrwrap CFRP for example, a carbon fibre reinforced plastic which is currently being used to strengthen buildings, however, there is scope for that material to be utilised similarly to CIPP liner, creating a strong and a more uniform, longer lasting, more durable and reliable material to line and repair defective sewers. This expansion could spell the end of excavation replacements unless for extreme cases.

Primarily, the future is in the hands of companies which chose to invest in how to best use and store the data produced by sewer contact. Companies such as WinCan who are developing ways to link sewer data in one location and make it easy to access.

Future research options

As established during the beginnings of this paper there are plenty of different options to be explored in the future. For example, Poland is in the stages of having to reinstall much of its sewer network. Further study into the actions of Poland has chosen to take, the methods and materials being used. This could teach other countries a great deal when looking to expand current networks. The long-term maintenance benefits, as discussed earlier, could also be a potential future examination. A critical look into the relationship between continued maintenance and the likelihood of severe defects forming could help utilities companies invest their budgets wisely into future proofing their sewer networks. It would help companies move forward into long-term strategies as recommended by Steffens (2018).

A look into the removal of CIPP liners and ways to improve the environmental impact of removal. This could also include a view to see if CIPP liners could be reused in any way for a different purpose, reducing the single-use resources.There are other testing methods that with more resources and time could be expanded to get a clearer image of the limitations and mechanical properties of the CIPP liners. Alongside cure testing, water tightness, and an expansion of the number of samples tested more testing could be complete to create a clearer life span expectance of the liner. Increasing the number of samples tested could help link some relationships with physical properties, such as the link of fibre spread and failure behaviour.

Overall, this process has many elements, all of which could benefit from further testing with the aim of improving and streamlining the process to reduce mistakes, increase accountability and enable time and money to be saves as well as other resources, the designs and on-site actions will be more reliable when based on clear guidance and unbiased decision-making tools.

Conclusions and Recommendations

Based on the discussion there are some key recommendations that this paper wishes to put forward. Primarily all 7 stages of the process could benefit from a data management tool which incorporates all processes. This could act as a large database including field of information on the physical pipe characteristics: age, diameter, depth, etc. The database could also include extra external information such as soil type, traffic weight, the ground water level at that location etc. Finally, the database could include an area for information regarding external work being done to the pipe such as CCTV videos, dates surveyed, and any defects found, any work done to the pipe and the corresponding dates. The combination of data will have the ability to create prioritisation values which will show which lines have the highest criticality, as well as helping with the allocation tool once the defect data has been inputted. This could also help show other engineers where infrastructure lies when future planning. However, this database would only be beneficial if information is updated when required.

WinCan has started to move forward with this data management tool, incorporating the CCTV videos, the defects and some key pipe data. By expanding the flexibility in the software and the amount of information the software can cope with and the automatic pre-input tools which would help mechanise the allocation process. This would help speed up the initial design process to a point it would only need reviewing at a high level instead of being required manually. The other key recommendation for this process would be an expansion and clarification of the Standards regarding the entire CIPP lining process. This would give technicians and engineers a level of accountability to follow the standards and receive more guidance if situations arise on site. This would limit the amount of variation between different installations and increase the likelihood of the liner passing all criteria if the process is followed as per the guidelines.

Overall, this research paper has found that although the CIPP lining trenchless method of renovation is the most environmentally friendly option for long term full pipe repair, there are improvements that can be made regarding the whole process which could increase the time, money and environmental friendliness of the method.

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N.B. With Standards, some are now superseded.

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Nomenclature

CIPP – Cured-in-place pipe

Sewer renovation technique consisting of the insertion of a flexible tube of carrier material impregnated with thermosetting resin which produces a structural pipe when cured (WIS 4-34-04, 1995)

Curing

Process of hardening resin, which may be completed utilising heat or exposure to light/UV (BS EN 13566-4:2002)