Development of a sealing material and robot for automatic socket rehabilitation of grey cast iron pipes in drinking water supply systems

ABSTRACT
The project DeWaLoP, led by Vienna Water, aims to develop a robot that is able to apply a sealing system to repair the joint sockets of pressure operating water pipes measuring about 1 m in diameter. To do this, a modification of the sealing material for inner surface application will be developed and a complex robot system will be designed to perform various tasks, such as inspecting, cleaning and restoring. Seven commercial sealing materials with a broad spectrum of mechanical and physical properties were tested. For this purpose, a series of tests was carried out to measure tensile strength, bending and adhesion; in addition, dynamic mechanical analyses, differential scanning calorimetry and thermogravimetric analyses were also conducted. A change in the mechanical and physical properties of these materials after water exposure could be observed. Furthermore, the surface preparation and remaining contaminants, e.g. rust, can affect the adhesion properties of the sealant. The plan is to develop a formulation of a matched material based on the results of these tests and the existing knowledge about the behaviour of sealing materials. The proposed in-pipe robot consists of three main subsystems: a control station, a mobile robot (similar to a vehicle) and a maintenance unit with a redevelopment system. An operator controls the movement of the cable-tethered robot system remotely from outside the construction side.

Key words | grey cast iron, in-pipe robot, lead joint socket, material properties, pipe rehabilitation

INTRODUCTION
Leakage is a problem in terms of wasting an important resource and it is also an economic loss in the form of damage to the supply system, as well as to the foundations of roads and buildings (Burn et al. 1999; Hunaidi et al. 2000). Water losses in Vienna’s official water supply system can mainly be attributed to roughly 100 km of grey cast iron pipes with lead joint sockets that are up to 150 years old (M. Werderitsch, 25-08-2010, personal communication). Up to the 1920s, sockets were caulked with a hemp pack and lead ring. The swollen hemp pack ensured sealing and the lead ring stabilised the hemp in the socket. Over time, however, the hemp pack deteriorated and the lead ring was displaced by pipe movements, which eventually resulted in leakage (Kottmann 1997). However, the metallurgical and static conditions of these grey cast iron pipes are uncritical.

These leakages lead to erosion of the pipe bedding and also impose stress on the pipe, which increases the likelihood of pipe breaks (Rajani et al. 1996; Burn et al. 1999). Vienna Water started a survey to investigate the relationship between traffic and the occurrence of grey cast iron pipe breaks. A significant coherence with truck traffic volume was observed, as well as an increased rate in the number of breaks in the area around crossroads (Magistratsabteilung 31 Wasserwerke 2009). Truck traffic volume will continue to be on the same level or even increase, therefore it is
important to repair leakages in time in order to avoid deterioration of the pipe embedment.

The project: developing water loss prevention

The research project ‘Developing Water Loss Prevention’ (DeWaLoP) funded by the Slovak-Austrian cross-border programme 2007–2013, ‘Creating the Future’, deals with the reduction of water losses through the rehabilitation of leaky pipe connections. The project, which is led by Vienna Water, aims to develop a robot that can crawl into water pipes of about 1 m in diameter and apply a sealing system to repair only the joint sockets of the pipes.

The development of a modification for a sealing material to be used on the inner surface of pressure operating grey cast iron pipes is a new field of research. The challenges of this endeavour lie in the numerous requirements that have to be met for the sealing material due to the boundary conditions in such a special environment. The main requirements are that the material be handled by a robot and a lifetime of 50 years for the material is expected.

Second, all the materials used have to be suitable for drinking water and conform to the drinking water ordinance (Umweltbundesamt 2010) in order to eliminate health risks to the end consumer, as well as the deterioration of its quality. Third, the material used in pressure pipes should have sufficient stiffness and strength. The pressure in distribution and supply pipes ranges from 0.4 to 0.6 MPa depending on the difference in altitude between the pipe and water reservoir. Pressure in the transport pipes can increase up to 1 MPa in the event of pressure surges caused by the abrupt closing of a gate valve (M. Werderitsch, 17-10-2012, personal communication). In addition, the material must show appropriate elasticity to compensate for elongation due to minimal pipe movements.

Rehabilitation carried out by operators requires that the pipes have a diameter of at least 0.8 m. The particular environment in the pipe is just one of the risks affecting the safety and health of operators. The robots available on the market are mainly designed for pipes with diameters ranging from 300 to 800 mm. To our knowledge there are no commercial robots working in pipes that are 1 m in diameter or larger. The DeWaLoP robot system is more complex than the typical commercial systems. It is designed to perform several tasks (inspect, clean and restore) instead of just one. The proposed solution consists of three main subsystems: a control station, a mobile robot (similar to a vehicle) and a maintenance system.

The benefit of the rehabilitation method described is that all of the working steps can be operated externally without any workers on the inside of the pipe. There are other commercially available functional sealing systems. For example, an EPDM sleeve clamped into the pipe with stainless steel rings fulfills all of the technical requirements, however, manpower is still required for the installation. Furthermore, an earlier investigation of a customised sealing system that failed after 2 years showed that both biological and environmental influences caused the failure (Lüftl et al. 2010). Unmanned, installable inliner systems failed after a short operating time. Some of the rehabilitation problems that can arise are the following: inexact alignment during the assembly, and variation of the socket gap around the circumference. Also, the pipes may run together; in practice, this means that the rehabilitation cannot be completed. In order to ensure successful implementation of the proposed rehabilitation method, a feasible socket gap is necessary.

EXPERIMENTAL

Materials

Material tests were carried out with seven different commercially available materials belonging to three main groups: polyurethane, epoxy and silane modified polymer. The acronyms used for each material are listed in Table 1. The materials of each group have different properties with regard to elasticity, stiffness, filler content, filling materials and resin mix (one component or two components).

Methods

By means of thermogravimetric analysis (TGA), the mass change of the samples as a function of temperature was examined. The initial condition of the cured material was investigated first, then the material after exposure to water was tested. Mass loss of up to 200 °C is considered for determining the water content of the sample. The TGA
experiments were carried out with a TGA 2050 (TA Instruments) using air atmosphere, a sample mass of approx. 50 mg, an alumina pan and a heating rate of 20 K/min from ambient temperature to 600°C.

Differential scanning calorimetry (DSC) measurements conducted in a DSC Q2000 (TA Instruments) were used to determine the glass transition temperature ($T_g$). The heating rate was 20 K/min and the sample mass was about 10 mg. The heating run defined for the materials was as follows: EP1, EP2, PUR3 – from 20 to 100°C; EP5 and PUR2 – from -40 to 80°C; PUR1 and SM1 – from -80 to 40°C.

The glass transition temperature ($T_g$) and the storage modulus ($E_0$) were also determined with dynamic mechanical analysis (DMA). In fact, the $T_g$ can be determined from the DSC data or DMA data at the maximum of loss modulus $E''$ and the loss factor tanδ. For rigid specimens (EP1, EP2, EP3 and PUR3), the DMA was used in a three-point bending mode (50 mm support span) and for elastic specimens (PUR1, PUR2 and SM1) in the double cantilever mode (35 mm bending length). All of the samples were measured with an oscillatory frequency of 1 Hz and a heating rate of 3 K/min and an amplitude of 70 μm. For the most part, the $T_g$DMA ($E''$) correlates well with the $T_g$DSC, but is always found on a lower level than the $T_g$DMA (tanδ) (Ehrenstein et al. 2003). Sample dimensions were 10 mm × 3 mm × 60 mm (width × height × length) and the measurements were taken with a DMA 2980 (TA Instruments).

Each thermal analysis measurement was repeated two times at least to check for reproducibility.

Tensile strength ($σ_M$) and strain at break ($ε_B$) were determined according to EN ISO 527 (EN ISO 527 1996). Each testing series consisted of 6 specimens of shape 5 A. The modulus of elasticity ($E_T$) was determined at a test speed of 1 mm/min followed by 50 mm/min for measuring the strength and strain at break.

The quasistatic bend test is used especially for testing brittle materials whose failure behaviour causes technical problems in tensile tests (Grellmann & Seidler 2007). To compare the modulus of elasticity and to show differences, a three-point bend test was arranged for the brittle EP1 and EP2 materials in accordance with EN ISO 178 (EN ISO 178 2010). The support span was 50 mm and the test speed was 8.4 mm/min (calculated from the DMA testing procedure: 1 Hz frequency and 70 μm amplitude). An extensometer was used for measuring the deflection at the middle of the sample. The dimensions of the samples were 10 mm × 3 mm × 60 mm (width × height × length). Six specimens of each series were tested.

An adhesion tensile test was arranged to gather information about the materials’ adhesion properties on differently prepared grey cast iron surfaces. For one series of specimens, all of the loose corrosion products were removed by using a wire brush; and for another series, the sample surface was grinded with a common angle grinder. The sealing material layer between the two grey cast iron ground bodies (dimension 20 mm × 20 mm) was 12 mm thick. The test speed was 5 mm/min and the adhesion tensile strength and strain at break were registered.

All the mechanical tests were performed using a Zwick & Roell, model Z050 machine.

### RESULTS

#### Material tests

Preliminary tests showed that the tensile test is not the method of choice for determining the modulus of elasticity, especially for brittle materials. Proper results can be achieved by dynamic mechanical analyses and bend tests. For the brittle materials EP1 and EP2, the results in Figure 1 (left) depict a good correlation of the modulus obtained by DMA and bend tests. Furthermore, after 28 days of exposure to water at a temperature of 40°C the modulus of elasticity of most of the materials was reduced by up to 50% in comparison to the initial condition. The epoxy materials EP1 and EP2 showed a strong decrease in the modulus of...
elasticity, but were still at a high level. Material SM1 is an extreme example with a modulus reduction of 75%. This effect can be explained by the water absorption properties of polymer materials, which is already known from the literature (Ehrenstein et al. 2005).

A decrease in mechanical properties after exposure to water can also be observed in the other materials by testing tensile strength. The initial condition (IC) tensile strength and the modulus of elasticity were measured on fully cured samples, which means that an increase in tensile properties cannot be achieved by additional curing.

The water absorption of the samples was determined by means of TGA. The results (Figure 1, right) show that no material is resistant to water absorption. Exposure at 7 °C leads to a lower absorption of water than exposure at 40 °C for the same duration. A higher temperature causes an increase in the diffusion rate, therefore some type of a time scaling effect can be arranged (Ehrenstein & Pongratz 2007). The strong decrease in the material’s SM1 modulus corresponds well with the highest water absorption of about 13% m/m. Hence, the material SM1 was rejected since a material with such properties is not suitable for application in a water environment.

The glass transition temperature \( T_g \) of a material defines the application temperature. Elastic materials are typically used above, and thermoset materials below, the glass transition temperature. In addition, the water absorption of a polymer results in a reduction of the glass transition temperature and changes in the application temperature range of each material analysed (Ehrenstein & Pongratz 2007). Under no circumstances should the application temperature and \( T_g \) be in the same range.

Figure 2 (left) shows the differences in the \( T_g \) values determined by different analytical methods. A good correlation between \( T_g^\text{DSC, IC} \) and \( T_g^\text{DMA (”)}, IC \) for the materials investigated can be observed. This is in accordance with the results reported for other materials by Ehrenstein et al. (2005). Therefore, for a follow-up investigation, the \( T_g \) from the DMA data at the maximum of loss modulus \( E^{”)} \) is used. The effect of water exposure on \( T_g \) of the materials is shown in Figure 2.

**Figure 1** (Left) Modulus of elasticity determined by dynamic mechanical analyses and bend tests, \( E_{\text{DMA, IC}}, E_{\text{DMA, WE}} \): initial condition, water exposure 28 days, 40 °C; \( E_f \): bend test, initial condition. (Right) Water content of all materials after 44 days of water exposure at 7 or 40 °C.

**Figure 2** (Left) Glass transition temperature \( T_g \), different analytical methods. \( T_g^\text{DSC, IC} \): from DSC data; \( T_g^\text{DMA (”)}, IC \): from DMA data at the maximum of loss modulus; \( T_g^\text{DMA (tan δ), IC} \): from DMA data at the maximum of loss factor. (Right) Glass transition temperature \( T_g \) change after exposure to water at 40 °C, initial condition is signed IC, water exposure WE.
(right). An overlapping of the application temperature range and $T_g$ can be seen for the materials EP3 and PUR2. Therefore, these two materials are no longer taken into consideration for application. Furthermore, the $T_g$ of material EP1 moves closer to the application temperature range. However, the mechanical properties still remain good.

In addition to common mechanical testing methods and thermal analysis measurements, an in-house developed adhesion test was performed. First, the adhesion strength and strain at break in tensile mode (Figure 3, left) were determined; second, the failure pattern of the specimens was analysed (Figure 3, right). Failure patterns were analysed according to EN ISO 10365 (EN ISO 10365 1995).

The results clearly show a massive difference in adhesive strength due to the surface preparation for materials EP1 and EP2. This can be explained by the failure pattern. Grinding as a surface preparation results in partial cohesive failure and the adhesion strength converges to the material’s tensile strength. Removing all of the loose corrosion products causes cohesive failure of the corrosion layer with lower strength than the sealant material (Figure 3, right, top).

Materials EP3, PUR2, PUR3 have low adhesion strength and show an adhesive failure pattern in both variations of surface preparation. This was a major reason to reject material PUR3. Furthermore, two materials (PUR1 and SM1) show complete cohesive or substrate near cohesive failure (Figure 3, right, bottom). With respect to temperature variation and subsidences in the pipe bedding, the sealing materials have to exhibit some elasticity in compensating for pipe movements. To determine the material’s deformability, common tensile tests were conducted and the strain at break $\varepsilon_B$ was determined. The strain at break $\varepsilon_{B,A}$ from the adhesive tensile tests was also analysed.

Figure 4 shows the correlation between $\varepsilon_B$ and $\varepsilon_{B,A}$, therefore the influence of the material’s usage on the strain at break can be determined. The adhesion test shows a strong decrease in the strain at break for materials PUR3 and EP2. Generally, complete deformability of a material could not be achieved with either the grinded surface or
the surface with the removed corrosion layer because of the untimely failure of the adhesive bond interface.

**DeWaLoP robot system**

The proposed solution consists of three main subsystems: a control station, a mobile robot (similar to a vehicle) and a maintenance system.

The control station is in charge of monitoring and controlling all the systems of the in-pipe robot. The main controller is composed of a couple of SBCs (single board computers), one is in charge of monitoring and displaying the video images from the cameras on a LCD display, the second SBC is in charge of the robot system’s remote control, which receives the information from the physical remote control (the joysticks, buttons and switches), in order to control the robot systems (Mateos et al. 2011a).

The mobile robot enables the in-pipe modules to move inside the pipe; in the same way, it carries the electronic and mechanical components of the system, such as power supplies, the restoration material tank and motor drivers. It uses a differential wheel drive, which allows the robot to quickly adjust its position in order to stay in the middle of the pipe while moving.

The maintenance unit refers to a structure that is able to expand or compress with a Dynamical Independent Suspension System (DISS) (Mateos & Vincze 2011b). By expanding its wheeled legs, it creates a rigid structure inside the pipe, so that the robot’s cleaning and restoration tools work without any vibration or involuntary movement from the inertia of the tools and accurately restore the pipe joint. At the same time, by compressing its wheeled legs, the wheels become active so the maintenance structure is able to move along the pipe alongside the mobile robot. The structure consists of six wheeled legs, distributed in pairs of three on each side and separated by 120°, which supports the structure along the centre of the pipe. The maintenance system combines a wheel-drive system with a wall-press system, enabling the system to operate in pipe diameters varying from 800 to 1,000 mm. Moreover, the maintenance unit and the mobile robot form a monolithic multi-module robot, which can be easily mounted/dismounted without the need for screws (Mateos & Vincze 2011c).

The vision system of the in-pipe robot includes a total of four cameras (Figure 5, left) in order to navigate, detect and redevelop (Mateos & Vincze 2011d). For the navigation stage, two cameras are required: one is located at the front to find the way into the pipe; the second is located at the back to find the way out. For the detection stage, an omnidirectional camera is located at the front end to enable detection of the pipe joint (Mateos & Vincze 2011e). Finally, for the redevelopment stage, another camera is mounted on the tool system, which enables the operator to follow the cleaning and restoration process in detail. The concept of the DeWaLoP redevelopment tool system mimics a cylindrical robot able to cover the 3D in-pipe space. The cleaning and sealing tools are mounted on one end of the H-configuration arm, while on the other end, a wheeled motor enables the tool system to rotate around the inner pipe surface, as shown in Figure 5 (right).

**CONCLUSION**

Due to the arduous working conditions within pipes in the resealing of leaking joint sockets, the aim of the research

---

**Figure 5** (Left) DeWaLoP 2D simulator. Vision system – Cf – front camera, Cb – back camera, Co – omnidirectional camera and Ct – tools camera. (Right) Redevelopment system.
project ‘Developing Water Loss Prevention’ (DeWaLoP) is to develop a highly automated (unmanned operation) robot system for grey cast pipes exceeding 800 mm in diameter. For this purpose, a new robot system has had to be conceived, which is able to crawl 100 m through a pipe and rehabilitate the joint sockets by applying a sealant. The following requirements should be taken into consideration in selecting the material for the sealant: drinking water suitability, a lifetime of 50 years, sufficient stiffness, strength and the appropriate elasticity to compensate for elongation. Seven commercially available sealing materials (based on three different polymer types: epoxy, polyurethane and silane modified polymer) were tested. A comprehensive characterisation of these socket sealing materials could be achieved since the test methods used covered a broad spectrum of mechanical and physical properties.

The TGA results of the materials after an immersion test show that the absorption of water corresponds with a decrease in the mechanical properties, such as modulus of elasticity and tensile strength. Obviously, water absorption causes a plasticisation effect in all the materials. In addition, a reduction in the glass transition temperature can be observed. This must be taken into consideration when it comes to selecting a sealing material since the application temperature range is about 7–18 °C. Furthermore, care must be taken with the surface preparation because it influences the adhesion/cohesion (fracture strength) of the sealant. The results of the adhesion using a tensile bond strength test indicate very clearly that insufficient removal of corrosion contaminants causes a reduction in adhesion strength, especially for brittle materials. Hence, an adequate pre-cleaning process of the socket must be carried out and this becomes a further challenge to the robot’s cleaning device.

Compared with common tensile tests, all of the materials show a lower strain at break in the adhesion tensile test. Studies of the failure pattern show that epoxy materials tend to partial cohesive failure and the adhesion strength converges to the material’s tensile strength. In fact, cohesive failure is the required failure mode.

After analysing all of the test data, the silane modified polymer was classified as not suitable for the intended use, while the epoxy and polyurethane systems showed some advantages. However, the results indicate that commercially available sealing materials do not adequately satisfy all of the requirements of this kind of application. Thus, in future, it will be necessary to develop a material formulation that matches all of the requirements for successful lead joint socket rehabilitation in grey cast iron pipes. Furthermore, the influence of corrosion has to be evaluated further. The development of a method for testing the materials’ pressure resistance in a pressure chamber is in progress. In this connection, material fatigue can also be observed by varying hydraulic heads.

In the conceived DeWaLoP system, an operator guides an in-pipe robot 100 m through pipelines from the outside. The mechanical system of the robot is flexible and can work in pipe diameters ranging from 800 to 1,000 mm. The restoration tool system developed for the robot is able to cover the inner three-dimensional in-pipe space by mimicking the cylindrical robot mechanism. The new robot combines inspection, cleaning and rehabilitation of the socket in one step and increases the effectiveness of the rehabilitation process.

ACKNOWLEDGEMENTS

This work is financed in part by the DeWaLoP project of the European Regional Development Fund, Cross-Border Cooperation Programme Slovakia-Austria 2007–2013 ‘Creating the Future’ and Vienna Water.

REFERENCES


First received 3 September 2012; accepted in revised form 7 November 2012