Physiochemical changes in London clay adjacent to cast iron pipes

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Abstract: This paper is based on ongoing research into the interaction between soil, in this case London Clay, and cast iron pipes. Current literature on this topic only focuses on the performance and failure of the pipe rather than on the pipe-soil system. Independent studies have observed that burst rates in cast iron pipes increase after periods of severe wetting and that these failures coincide with areas of clay soil, and in particular London Clay. The hypothesis of the current research proposes that in fact the soil is the significant contributor to the failure mechanism.

Buried cast iron water mains are influenced by a number of parameters, which can be categorised as those deriving from internal sources or external sources and those due to the pipe material. Many of the influences vary with time and interact with each other. The result is a complex, and time dependent, system of physical and chemical influences on a buried pipe. The notably higher incidence of bursts in London Clay suggests that this clay is a relatively aggressive soil, and that its particular physiochemical constitution has a more detrimental effect on cast iron than other soil types.

This paper describes a series of laboratory tests that have been designed to investigate how the physiochemical properties of London Clay change with time close to cast iron pipes. Three main test arrangements have been used. The first test arrangement uses cast iron rods in consolidated clay samples, with the objective of providing an indication of corrosion activities with time. The second test arrangement involves the use of an electric current between the cast iron and the clay to increase the rate of corrosion and is designed to investigate the properties of the soil after the migration of the corrosion products. The third test arrangement uses a 'U' shaped piece of cast iron that can be stressed to different levels and is designed to investigate the effect of stress on the corrosion rate. Preliminary results from these tests are presented and discussed.

Résumé: Cet article aborde le problème des interactions entre le sol et les canalisations en fonte. Jusqu'à présent, les recherches publiées sur ce sujet, n’ont traité que des performances et des défauts des canalisations, mais peu d’études ont été réalisée sur l’interaction sol / canalisation. Seules quelques études isolées ont observé que le taux d’éclatement des canalisations augmente après une longue période humide et que l’apparition de ces problèmes coïncide avec les zones où le sol est argileux (plus particulièrement Ldon Clay). L’hypothèse avancée ici est que le type de sol pourrait avoir une incidence néfaste sur les canalisations.

En effet, les canalisations souterraine d’eau sont soumises à l’influence de plusieurs paramètres; ceux-ci peuvent être internes, externes ou peuvent provenir de la nature du matériau de la canalisation. La plupart de ces paramètres varient avec le temps et peuvent interagir entre eux. Il s’agit donc d’un système complexe de paramètres physiques et chimiques agissant sur les canalisations souterraines. En outre, le fort taux d’éclatement recensés dans les canalisations en contact avec de London Clay suggère que cet éclatement serait dû à un sol plus agressif dont les propriétés physico chimiques auraient des effets plus nocifs que les autres sols.

Afin d’étayer cette hypothèse, une série de tests a été réalisée dans le but d’observer les changements avec le temps de la composition de London Clay en contact avec les canalisations en fonte. Trois tests ont donc été effectués: Le premier test utilise des tubes en fonte immergés dans London Clay consolidé. L’objectif de ce test est de fournir des indications sur les activités corrosives dans le temps. Le deuxième test introduit l’utilisation d’un courant électrique entre la fonte et l’argile pour augmenter le taux de corrosion. Ce test a été effectué afin d’examiner les propriétés du sol après la migration des produits corrosifs. Pour le troisième test, une pièce en fonte en forme de U pouvant subir des contraintes de différents niveaux a été fabriqué pour observer les effets de ce stress sur le taux de corrosion. Les premiers résultats de ces tests sont donc présentés et développés.

Keywords: clay, laboratory tests, pipelines, soil-structure interaction

INTRODUCTION

Water is a vital part of every day life and therefore the water supply has to be reliable. Cast iron has been used widely in the UK and the rest of the world for water supply networks. Although new pipeline materials such as high density polyethylene are used today, cast iron pipelines still make up a large part of the network. It has been observed that cast iron pipes have a very high failure rate in some soils, such as London Clay. This causes both problems and costs, through the management of maintenance and replacement of pipes.

Pipeline failure occurs for many different reasons, but external corrosion and ground movements are prominent factors (see Figure 1). However, this figure is likely to refer only to the dominant cause of failure and so combinations of these causes would not be shown. For example, corrosion could weaken the pipe before failure occurs as a result of a second cause, say ground movement. This figure does, however, show failures are influenced by the bedding soil. Therefore, the two most important processes in a soil defining its corrosivity and the causes of ground movements, need to be better understood if prediction tools, and hence better management systems, are to be implemented.

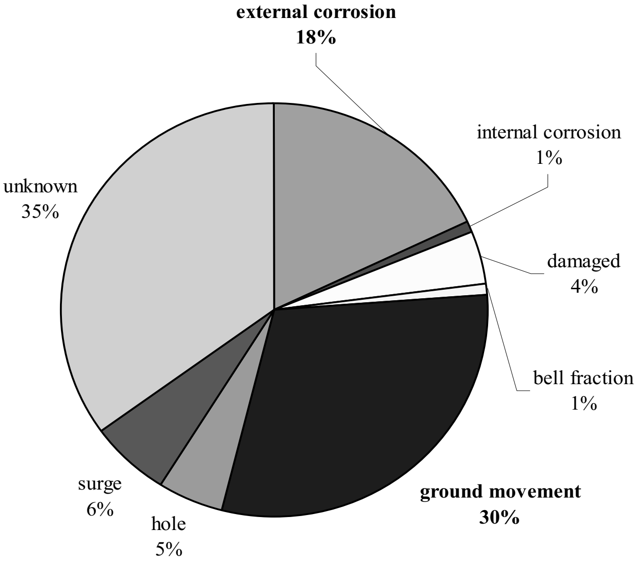


Figure 1. Causes of Failures of Cast Iron Pipes (after THWS Repairs Database, 1999)

At the time when most cast iron pipelines were installed, the practice was to use the trench excavation material as the pipe backfill. Every soil has its own physical and chemical properties and therefore pipes are exposed to different levels of aggressive environmental conditions, which may change over the length of the pipeline. A significantly higher number of failures have been noticed in cast iron pipes placed in clays, although it is equally evident that not all clays are equally aggressive. Cast iron pipelines placed in London Clay, in particular, have higher failure rates than pipes in other clays and it is this specific pipe – soil combination that has been adopted as the focus of the research project reported here. It is clear from this discussion that to provide effective protection to the pipe material against environmental conditions a better understanding of the failure mechanisms have to be gained and that the soil plays a major role.

THEORETICAL BACKGROUND

Complexity of the Pipe – Soil System

The water supply system is a major part of the underground infrastructure in every modern urban development. This system should ideally work without any faults and with low maintenance to meet the goals for a reliable water supply, low costs and minimal disturbance of other utilities. In the UK the current pipe networks have great variation in pipe materials, ages and bedding conditions. Over recent decades pipe manufacturing methods have improved, new pipe materials introduced and installation techniques changed. The result is a network with a large range in quality across one system. However, the water supply system can only work efficiently if all parts work together.

The pipe-soil interaction behaviour includes a lot of different processes and is therefore a very complex system. In addition, chemical and physical properties of the pipe material and surrounding soil change over time. Many tests have been carried out to understand the different failure mechanisms of the pipes alone, such as the four-point bending test and ring test. Both tests are mechanical laboratory tests carried out on pipes and test the pipe to failure. However, the pipe and the surrounding soil behave as one system and fail together. An improved knowledge of the processes taking place at the soil - pipe interface would help in the understanding of the failure mechanisms likely to be occurring. Those different failure mechanisms are dictated by the surrounding soils differing both between soil types and, in the case of clays, within soil types. This is evident from what has been presented above.

Types of Corrosion

Pipes fail due to corrosion alone, but pipes that are weakened through corrosion then fail more easily under externally applied stresses. Hence, corrosion is one of the most important aspects of the interaction behaviour between the pipe material and clay. Cast iron has similar corrosion behaviour to other metals or alloys and thus is susceptible to the following corrosion mechanisms:

- Uniform or general attack
- Galvanic or bimetallic corrosion
- Graphitic corrosion (special type of galvanic corrosion)
- Pitting and crevice corrosion
- Bacterial corrosion in anaerobic conditions

- Stress corrosion or corrosion fatigue
- Erosion-corrosion
- Fretting corrosion
- Intergranular corrosion

The causes of corrosion in soils are complex and originate from a wide variety of mechanisms. Characteristically the corrosion is almost always non-uniform because of the nature of soils. Different types of soil yield different degrees of aggressivty to the pipes. For example the progress of corrosion in well drained soils, such as sand and gravels, will be very slow, these soils being said to have a high resistivity. However, soils like those in marsh environments, acid soils, fills containing clinker and generally soils of high electrical conductivity cause more rapid corrosion, while very rapid corrosion may also occur in heavy clay deposits. In addition, corrosion rates are often increased by the activity of sulphate-reducing bacteria (Dawson, 1978).

Corrosion associated with Cast Iron buried in Clay Soil

Not all the corrosion types listed above are relevant for corrosion attacks on cast iron pipes buried in clay. The first six corrosion types cause corrosion in cast iron pipes and therefore this research will only focus on these. However, graphitic corrosion is a special case of galvanic corrosion as it occurs between the components of cast iron: iron (anode) and graphite (cathode). This process, in which the pipe material becomes a galvanic cell, is independent of the influence of the soil and as such is not a primary feature of this research programme.

The uniform or general corrosion attack is a less aggressive form of corrosion compared to non-uniform types. It will weaken the pipe uniformly, but pipes are provided with thicker walls to accommodate the loss of a certain amount of material from corrosion and thus this type of corrosion is effectively allowed for in the pipe's design. The amount of material lost will be reflected in the weight or volume loss of the pipe after cleaning the corroded surface. The average corrosion rate of unalloyed cast iron in soil will be less a 0.25mm per year (Dawson, 1978).

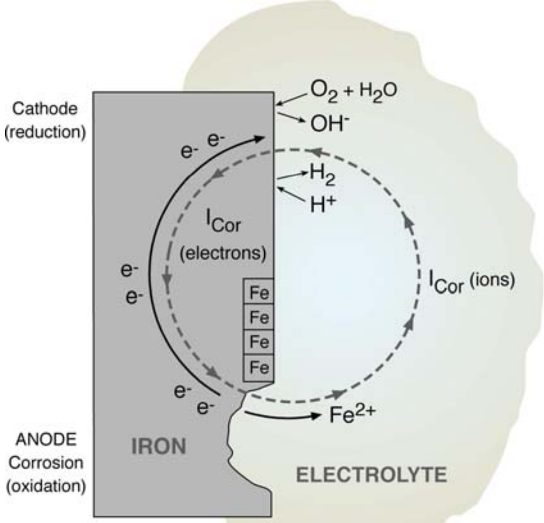


Figure 2. Galvanic cell (www.npl.co.uk)

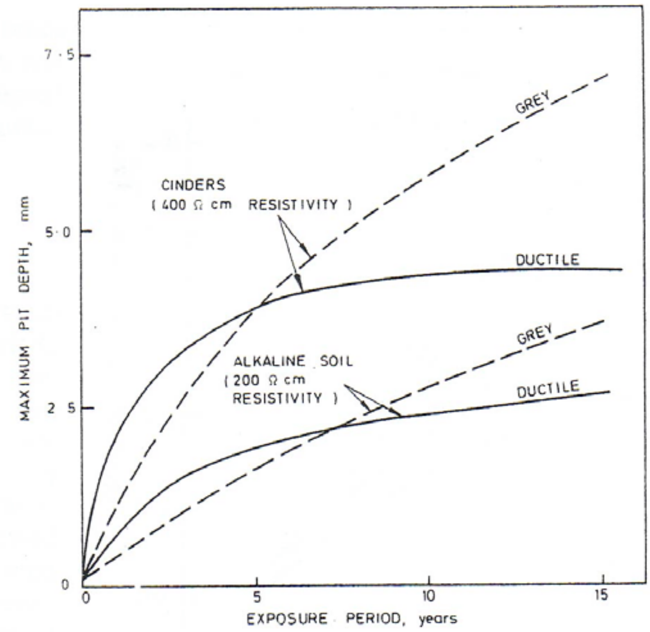


Figure 3. Increase of maximum pit depth with time (Fuller, 1972)

The corrosion process of cast iron is an electrochemical process with an anodic reaction where metal oxidises, with a corresponding and equal cathodic reaction, according to which oxygen is often reduced (reaction 2b). A galvanic cell will build up between the cast iron (anode) and the clay (cathode). Figure 2 shows the principle of a galvanic cell. The most common and important electrochemical reactions in the corrosion of iron are:

Anode: $Fe \equiv Fe^{2}+ + 2e^{-}$ (1)
Cathode: $2H^{+} + 2e^{-} \equiv H_{2}$ or (2a)
$\frac{1}{2}O_{2} + H_{2}O + 2e^{-} \equiv 2OH^{-}$ (2b)

Reaction 2a is most common in acids and 2b is the common reaction in a pH range of 6.5 – 8.5.

Nevertheless, corrosion processes in soils are mainly non-uniform and the non-uniform loss of material being far more harmful to the performance of the pipeline. The wall thickness and the pipe material determine the resistance of the pipe against internal and external influences, such as applied stress, and the stress increases dramatically in the pipe walls if the wall thickness is reduced in a non-uniform way. The thinner parts of the pipe wall experience higher stresses and succumb more easily to fatigue.

Corrosion under stress, or under the influence of sulphate reducing bacteria (see below), causes the formation of pits; a form of non-uniform corrosion. The pits constantly grow in grey cast iron over time and these local weaknesses can ultimately result in pipe failure (Figure. 3). The resultant failure can either be the result of corrosion directly (e.g. loss of a plug of material from the pipe wall) or weakened pipes can then fail due to ground movements. However, corrosion products, although symptomatic of corrosion, remain relatively strong and can reduce corrosion progress. Therefore, failure due to corrosion alone is relatively rare. Weak pipes normally fail due to ground movements, i.e. through the swelling and shrinking movements of clays or possibly lateral stress relief due to local excavation or erosion.

Sulphate reducing bacteria (SRB) are anaerobic bacteria, which means they live best under the complete absence of oxygen and at temperatures from 25° to 35°C, although some bacteria can also survive at more than 60°C. SRB have been implicated in the corrosion of cast iron and steel, ferritic stainless steel, 300 series stainless steels (also very highly alloyed stainless steels), copper nickel alloys, and high nickel molybdenum alloys (http://www.corrosion-doctors.org/). Sulphate is a very common natural component of the earth's environment, and is often bound in minerals or dissolved in water. Calcium sulphate, for example, is slightly soluble in water and therefore sulphate is contained in many lakes, rivers, oceans and groundwater. Chemically, sulphate consists of one sulphur atom which is surrounded by four oxygen atoms. SRB are able to strip away these four oxygen atoms leaving the sulphur ion. This free oxygen can then oxidise iron, i.e. corrode the iron. In order to prove the existence of SRB, sulphur needs to be found in chemical analyses of the clay near to the pipe.

Corrosion under stress is also known as stress corrosion cracking. This type of corrosion shows V-shaped fissures, which are formed orthogonally to the direction of local tensile stresses and have been identified as a cause of grey cast iron pipe failure (Palmer, 1982). It occurs under the combined effects of corrosion and stress, i.e. failure in this way cannot occur under the influence of stress or corrosion alone. A certain level of stress is necessary before stress corrosion can take place (min. stress in Figure 4); below this stress level stress corrosion is not expected. The initial growth of the crack increases with corresponding increases in the stress, as modelled in Stage 1. In Stage 2, the crack grows independently from the stress, while in Stage 3 the material is too weak to carry the stress and it will rapidly fail. The corrosion progress is dependent on both environmental conditions and temperature. In Stage 1 the grooves start to grow in a crack-like shape. After they have grown enough to be visible, they have a V-shaped groove which are normally very narrow but deep. Both the extension and the whole groove will gradually penetrate into the wall until failure occurs. These crack-like extensions form by corrosion around the graphite flakes and widen by continual corrosion attack. The rate of corrosion progression is naturally greater in more aggressive environments.

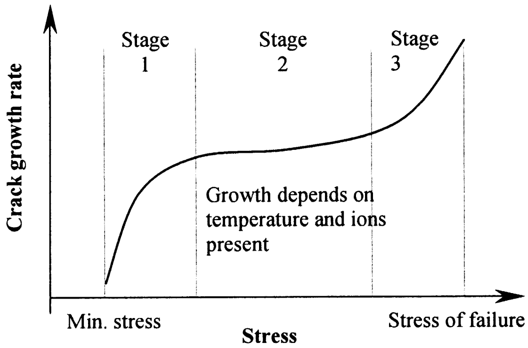


Figure 4. Growth rate of stress corrosion (www.azom.com)

METHODOLOGY

Tests on existing pipelines are very difficult to carry out because they are mostly placed under streets in urban areas. Sampling and testing *in situ* is therefore generally only possible if replacement or maintenance work is being carried out, and samples of pipes gained in this way are likely to be variable due to different local conditions (i.e. non-uniform along its length). This makes it difficult to get sufficient high quality samples from which to obtain constant data. Similarly the backfilled clay varies greatly in its properties and it is therefore difficult to distinguish changes of clay properties due to the impact of the cast iron pipes. Therefore, tests on clay in contact with cast iron are far easier if it were possible to simulate corrosion processes under controlled laboratory conditions. For these reasons three different series of laboratory test arrangements were designed as part of the current research.

Soil preparation

The soil used in all experiments was prepared in the same way. London Clay from a pipe replacement site in north London was used. The site is in an area of high pipe failure; therefore it is assumed that the clay is highly aggressive. The clay was dug out of the trench in large lumps, taking care that the clay was not in direct contact with the pipe to minimize contamination with corrosion products from the pipe. The material was then packed in plastic bags for transport and storage.

The first step of processing the clay was drying. Air drying was chosen, to avoid the possibility of high temperatures changing the chemical properties of the clay, and the clay was cut into small pieces to increase the surface area and decrease the time needed. A textile was placed over the drying clay to protect it against particulate contamination from the air. The dried material was then crushed.

The next step after crushing was sieving to remove the small amount of larger particles (• 2.0mm), as this would make it easier to obtain a more homogeneous samples during the consolidation process. The resulting London Clay contained a high clay content and all the soil properties subsequently referred to are related to this sieved material (Figure 5). It was assumed that even though the larger particle fractions were removed, the in situ conditions of the clay would still be accurately simulated.

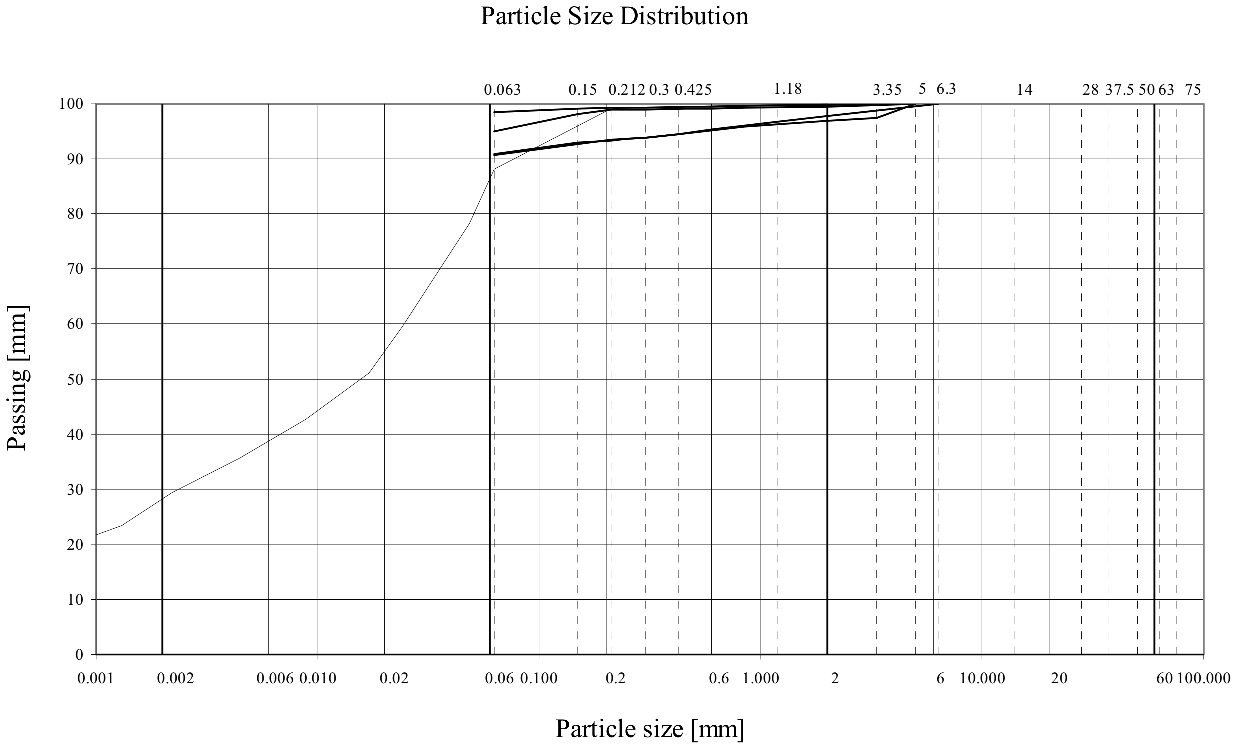


Figure 5. Particle size distribution of the in situ London Clay used in the experiments

The next step was to consolidate the samples. The consolidation conditions were chosen to create a homogeneous material with properties close to those measured in the field. The clay around pipes would have originally been compacted when the pipes were installed, but compaction would not give the homogeneity of the clay needed in the experiment. Changes in the clay due to the contamination with corrosion products were expected to be small and it would be difficult to detect them accurately in a non-homogeneous material.

Tests on the in situ material yielded a moisture content, w of 30-35%. The water content was chosen as the predominant property, because the conductivity is dependent on the water content and the amount of dissolved minerals. Corrosion, as an electrochemical process, also has a strong relationship with these soil properties. In addition, the preconsolidation pressure of the in situ material was measured as σ = 120kPa, which was therefore chosen as the maximum consolidation pressure. The consolidation steps for all tests were 5kPa for 2 days, 10kPa (2 days), 25kPa (4 days), 50kPa (4 days) and 100kPa (8 days).

A soil with a moisture content of 50% was created at the end of the consolidation process. This was slightly higher than the in situ water content, but the clay immediately around the pipes *in situ* was found to be very weak compared to soil further from the pipe and, since it helped to increase the corrosion processes, this higher water content was considered to be justified.

A slurry was mixed from the dried, and sieved, clay and deionised water. The water content chosen for the slurry was 100%. The soil water at this point contained exactly the same minerals as the in situ soil, because they did not get lost during the drying processes and no additional ions were introduced in the added water. During the consolidation process water with dissolved minerals was pressed out; however measurements showed that only a small percentage of the original mineral content was removed in this way.

The consolidation took place in two differently sized apparatuses. The two sizes, with diameter of 158.6mm and 277.6mm, were necessary for the different test arrangements. Generally, the consolidation apparatus was built in three parts (Figure 6). A small bottom part, which contained sand as a bottom filter, the middle part, which contained the soil sample and was taken out after the consolidation was finished, and the top part to hold the slurry at the beginning of the consolidation process and the filter with the top cap. The three parts were held together with silicon sealer and vertical steel rods outside the tube.

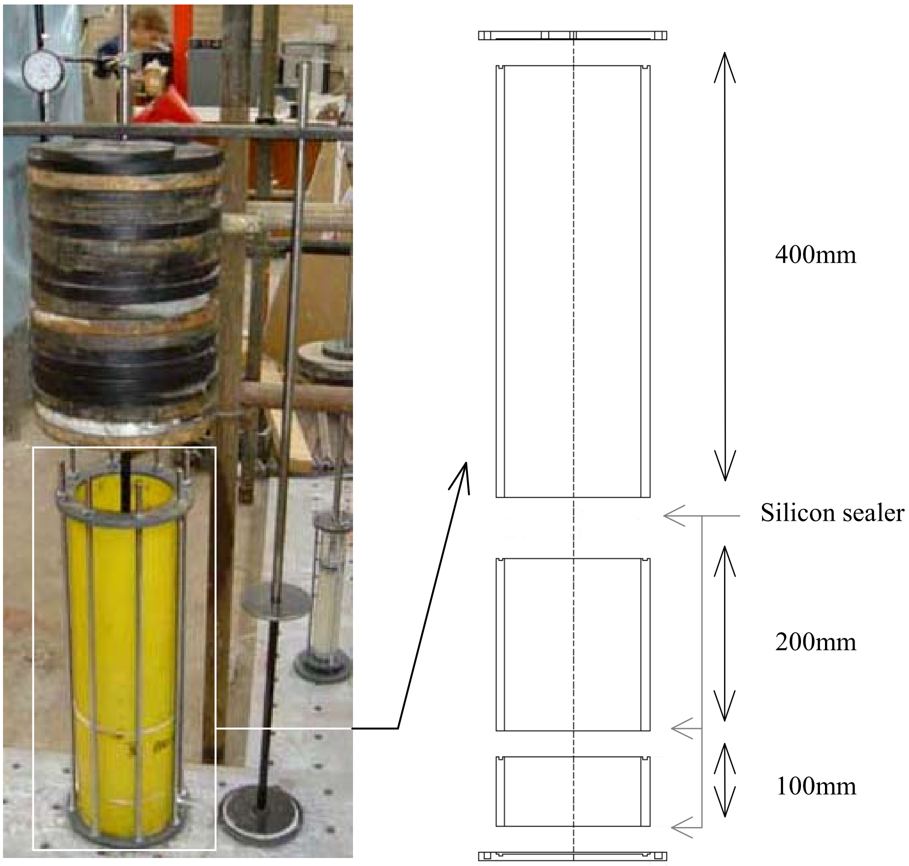


Figure 6. Consolidation equipment under load and cross-section sketch

First test arrangement

These tests were designed to simulate the natural corrosion under laboratory conditions. A larger container (277.6mm diameter) was used for these tests. After the consolidation had finished the 200mm high central section with an undisturbed clay sample was taken out of the consolidometer. The centre of the clay was cut out with a tube and replaced with a 24mm diameter cast iron rod (Figure 7). The top and bottom of the tube were then sealed with plastic plates. The top plate had small holes drilled every 10mm radially from the centre (Figure 8) so that it was possible to measure the electric field developing between the cast iron and the clay without opening the sample.

Figure 7. Clay sample containing the cast iron rod

Figure 8. Open sample after measuring the electric properties between the cast iron rod and the clay

Second test arrangement

The second test arrangement was designed to increase the corrosion rate and the migration of ions into the soil. 200mm high samples with a diameter of 158.6mm were chosen for this test. The undisturbed sample was taken from the consolidation equipment and placed between two cast iron plates. Both plates had holes drilled in them to facilitate water flow created by the introduced electric field. The bottom plate was fixed to the tube, while the top plate was able to move to accommodate possible soil movements. A small water reservoir was installed above the top plate and filled with deionised water during the test (Figure 9).

Figure 9. The second test arrangement

The initial measurements from the first test arrangement showed a voltage of around 0.5V was developed. For the second series of tests a fixed voltage of 5V (10 times that naturally developing) was chosen between the top plate (anode) and the bottom plate (cathode). The current dropped slowly as the test progressed, because the minerals moved to the bottom part of the sample and the new water drawn into the sample from the upper reservoir was deionised (Figure 10). The whole test was conducted under a constant temperature of 5°C.

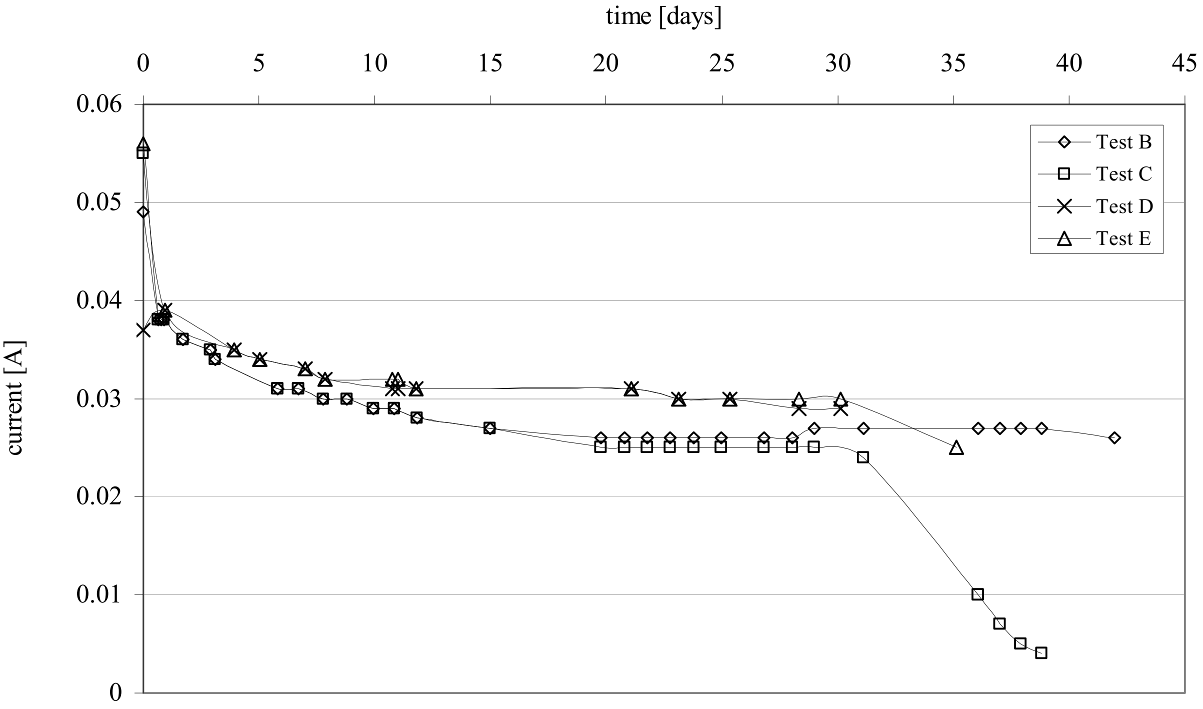
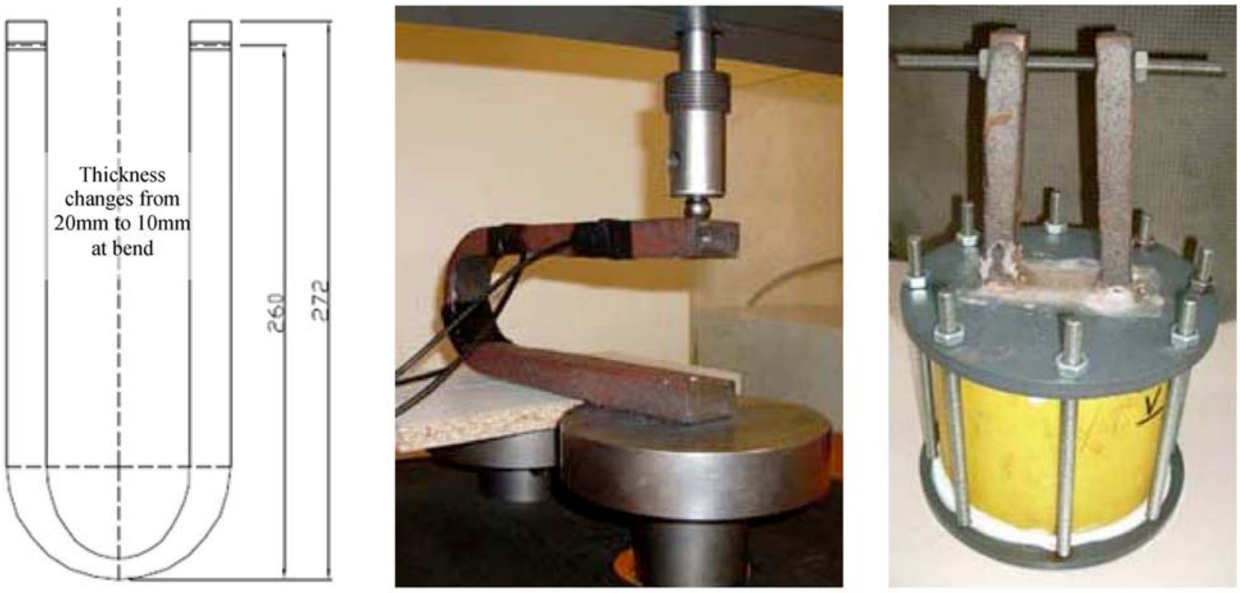


Figure 10. Changes of the current over time and at a constant voltage of 5V

Third test arrangement

The third test arrangement was set up to show the increase in corrosion under different stress levels. Cast iron was cast in a “U”-shape specimen, with the bend of the “U” being one half of the thickness of the rest of the specimen (Figure 11). Stress is induced in the specimen by pressing the two ends together. The specimen was then buried in consolidated clay.

To determine the maximum allowable stress, two of the "U" shapes were put under stress until failure and the stress-deformation curve was measured. Both samples failed under a similar load of approximately 970N. The stress corrosion behaviour was recorded at 50% and 80% of the failure pressure, the required deformation being taken from the curves shown in Figure 12.



(a) (b) (c)

Figure 11. U-shaped specimen for stress dependent corrosion tests (a) drawing of the design, (b) failure test on U-shaped specimen, (c) buried U-shaped specimen with a bolt to apply stress.

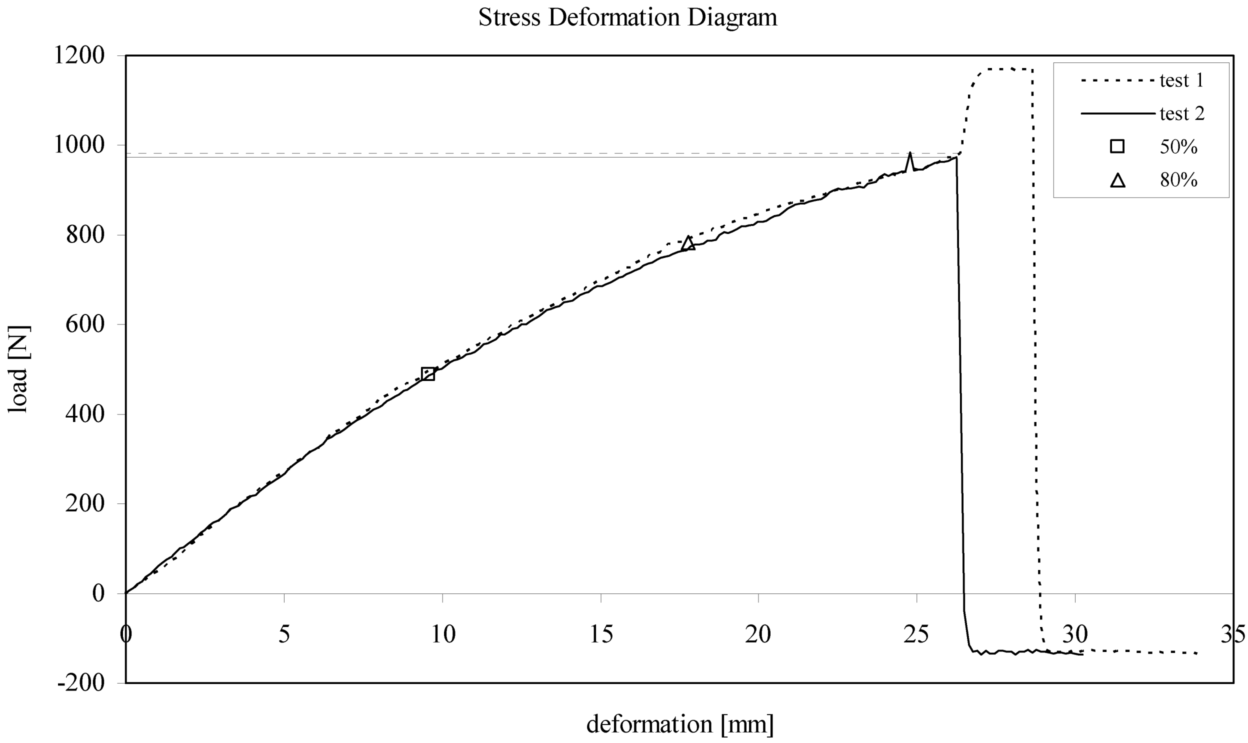


Figure 12. Load-deformation curve of the U-shaped specimen

INITIAL RESULTS

The results presented in this paper are from the second test arrangement. The two other tests are currently still running and results are expected in early 2006. The first results are from Tests B and C, both tests being treated with 5V for around 40 days (Figure 10). After the treatment the samples were opened and the soil was taken out in layers

20mm thick. Measurements of water content, cone penetration, conductivity and pH were taken for each of the layers, the results being presented in Figure 13. The measurements of the cone penetration were made using a 30° cone weighing 80g and being in contact with the exposed surface of the clay prior to being released to penetrate the clay under self weight for 5 seconds, the values providing an indirect measurement of undrained shear strength. The pH measurements were made with an “Orion 520A” device while the conductivity measurements were made with a “Hanna HI 9033” device. The left hand side of the Figures 13 (a) and (b) refers to the top of the sample, where the anode was. The original measurements immediately after consolidation are symbolised with thin lines linking two points only for each of the different tests. Both tests show a very similar behaviour.

The bottom 50mm of each sample became very hard and brittle. The penetration decreased greatly, and the pH and conductivity correspondingly increased markedly. The water content did not change significantly during the tests (bearing in mind that the water contents were relatively high initially) and therefore these changes are likely to be chemical related. One possible interpretation is that the dissolved minerals moved down through the sample with the water stream and crystallised there, this zone being characterised by a high pH. The very acid pH values for the rest of the sample were caused by the acid front emanating from the anode. In addition, the images of the sample show the difference between the top part and the bottom part of the sample, the parts being divided by a very thin dark line (Figure 14). It is possible that the line was created by iron ions coming from the anode, although detailed analyses have yet to be done to establish this. The minerals made the clay so dense in the zone beyond the dark line that the ions were stopped from further movement towards the cathode.

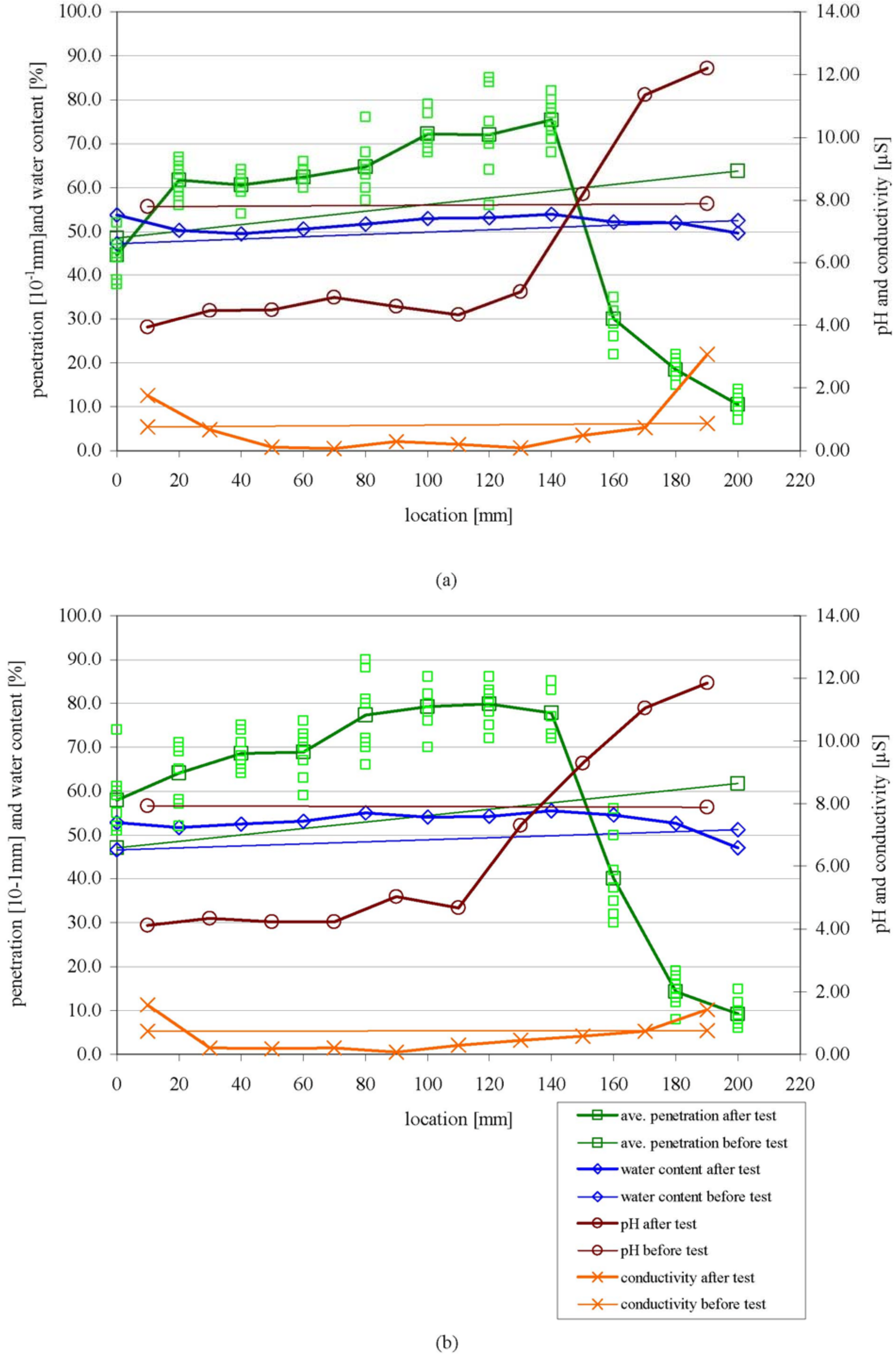


Figure 13. Measurements of penetration, water content, pH and conductivity for (a) Test B and (b) Test C

Figure 14. Photograph of the sample retrieved from Test B at the end of the treatment – cross-section

Further results

Investigations on Sulphate Reducing Bacteria (SRB)

London Clay is a very 'heavy' clay in which there is little oxygen present. These are the conditions in which SRB thrive, because they live in anaerobic conditions. Scanning Electron Microscope (SEM) images were taken from undisturbed samples of the clay from the trench and from samples directly in contact with the pipe surface. The samples from the trench material showed normal clay structures, as shown in Figure 15. However, the clay on the surface of a ca. 60 year old cast iron pipe showed very different structures (Figure 16). Not only do clay minerals exist, but several additional mineralic structures are also evident. Framboids are the most interesting of these structures. These are round structures (framboidal pyrite) shown in Figures 16. Framboids are created by SRB as the product of the sulphate reducing processes. The images therefore show the existence of SRB in the London Clay tested. Hence, the cast iron is exposed to a second very aggressive type of corrosion.

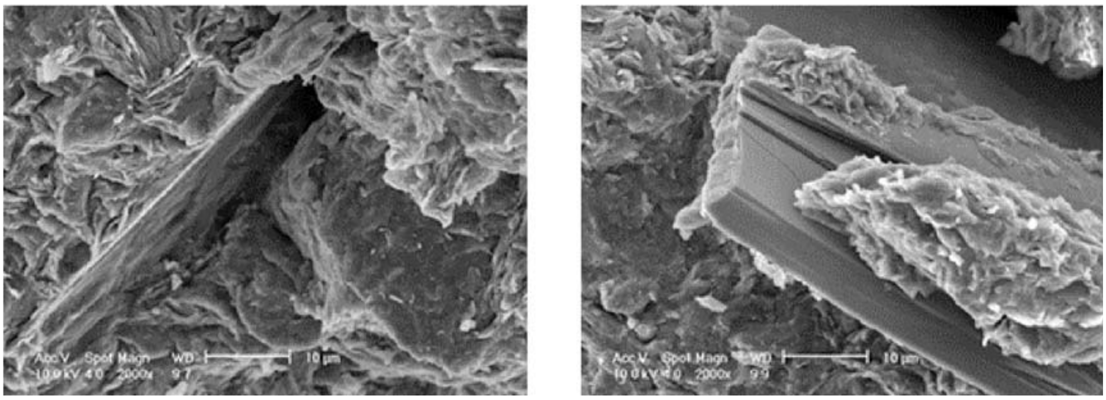


Figure 15. SEM images of the London Clay backfill material

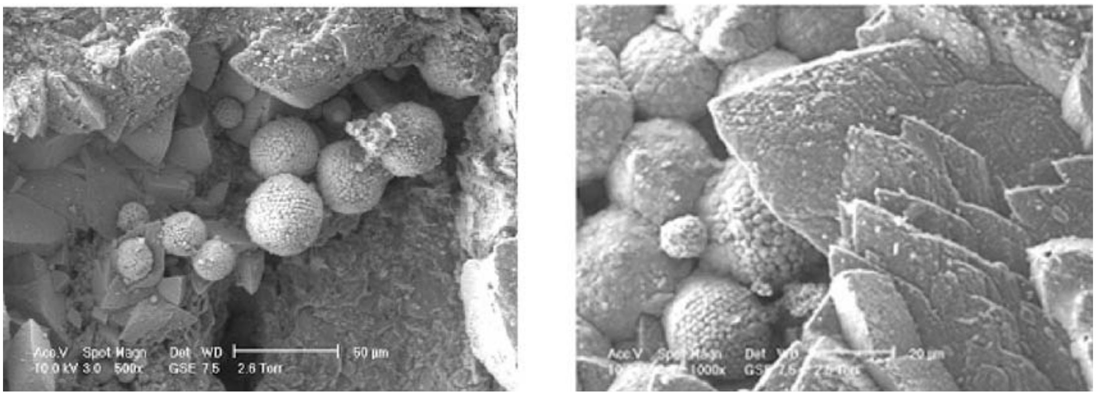


Figure 16. SEM images of the London Clay at the interface with the cast iron

Swelling and Shrinkage

Soil movements are a common cause of pipe failure. Swelling and shrinkage activities can be very considerable in clays, with these properties being related to the clay minerals. The main clay mineral in London Clay is ilite with a very high surface activity, although there is also smectite present. Linear shrinkage tests on the London Clay showed a very large degree of shrinkage (more then 17%). The expected swelling pressure in this clay due to water content changes is therefore high. Tests on the swelling pressure are currently being carried out.

CONCLUSIONS

Three types of test have been designed and developed to evaluate the aggressive types of corrosion of cast iron in contact with clay soil. Initial results of the test with additional electric voltage show significant changes in the properties of clay adjacent to the cast iron. Corrosion is taking place and iron ions are migrating into the clay, however dissolved minerals in the pore water are also moving and/or crystallising close to the cathode. SEM images show the existence of sulphate reducing bacteria, providing a very inhomogeneous and aggressive corrosion type. Swelling and shrinkage have the potential to cause large soil movements of pipelines buried in London Clay and thus contribute to pipeline failure. London Clay is a particular aggressive environment for cast iron pipes.

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