EFFECT OF CHLORINATED WATER ON THE OXIDATIVE RESISTANCE AND THE MECHANICAL STRENGTH OF POLYETHYLENE PIPES

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ABSTRACT

The effect of disinfectants was determined on the mechanical and chemical resistance of high-density polyethylene pipes, commonly used in modern urban networks for water conveyance. A fully monitored test plant was built able to simultaneously expose both pipe sections and pre-cut dog bone specimens to chlorinated and non-chlorinated water. PE100 polyethylene pipes for alimentary use with a nominal diameter DN 32 were tested in two sets of experiments involving both chlorine dioxide (at a constant concentration of 5 ppm), and sodium hypochlorite (at a constant concentration of 2.5 ppm). The effects of these disinfectants were assessed using monotonic tensile tests on dog bone specimens and oxidation induction time tests. Pressure tests at a constant temperature were also performed to assess any damage in the pipe samples after one year of exposure to chlorine dioxide. The results from the tensile and oxidation induction time tests showed that chlorine dioxide was the most aggressive disinfectant. Nevertheless, the pressure tests at a constant temperature did not show any failure of the pipes after 2000 hours of exposure.

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1. INTRODUCTION

High-density polyethylene (HDPE) pipes have been widely used in recent urban networks for water conveyance due to their advantages in terms of setting up, joining and toxicology safety. In addition, polyethylene pipes have a long life.

Chlorine disinfectants are commonly used in urban networks for water conveyance to ensure water potability and quality for consumers. Such treatments provide high germicide power, reliability, and efficiency. The effect of the treatment is steady, thus it can be also applied for wide networks. However, free chlorine released by the disinfectant produces a strongly oxidative environment, which affects all the components in the network. The oxidative effect is more severe with increasing temperatures.

Like many plastic materials, polyethylene is highly susceptible to oxidative environments, which can reduce both the strength and durability of the materials. The degradation of polyethylene and in particular HDPE, has been previously studied by many authors. [1] and [2] show that chlorinated water either significantly reduces the lifetime of HDPE pipes or promotes rapid antioxidant consumption. In contrast, in [3] no degradation was observed on HDPE pipes exposed to chlorinated water. As presented in [4] and [5], also cross-linked polyethylene (PEX) is affected by exposure to chlorinated water, which decreases the mechanical properties and lifetime of the material. An extrapolation technique to determine the lifetimes of PE100 and PVC-U pipes exposed to oxidative environments is proposed in [6]. In [7], a comparison between the ageing mechanisms of plastic piping materials both exposed to field conditions and to accelerated tests is presented. In [8] and [9], an investigation on the degradation of PE films and PE pipes exposed to chlorinated water is reported.

The vast majority of studies thus appear to agree on the aggressiveness of chlorine on the chemical integrity of PE. In contrast, the mechanical degradation of PE by chlorine exposure has not been unanimously recognized.

The two aims of the study were as follows: firstly, to assess whether chlorine, as used to assure water potability, affects the structural and chemical integrity of polyethylene pipes; secondly, to compare different disinfectants in order to classify their aggressiveness on polyethylene. The rationale behind the research is the large difference observed in the average lifetime between PE pipes of the same material lying in different positions along a conveyance network and exposed to different disinfection modes. Many failures were observed by a local multi-utility company (supplying potable water and other services), which supported this research. Similar failures have also been reported by other researchers [9-11]. It has been observed that failures, which always appear brittle, particularly affect pipes with a small diameter and thin pipes that transport chlorine dioxide disinfected water.

The study was performed in three steps: the design of the experiment, the design and construction of an ad-hoc experimental test plant, and the execution of a systematic experimental campaign. In the first step, all the factors involved in the interaction between the disinfectant and the PE pipes were identified and their range of variability was established. In the second step, the test plant was designed and built. In the third step, a systematic experimental campaign was run on the test plant. The campaign took into account chlorine dioxide and sodium hypochlorite, and lasted one year for each disinfectant.

All the specimens extracted from the plant during the experimental campaign were characterized mechanically by monotonic tensile tests and chemically by oxidation induction time (OIT) tests. The monotonic tensile tests were performed on dog-bone specimens (to ISO 6259 [13-14]), loaded up to complete failure. A batch of pipe samples exposed to chlorine dioxide was also submitted to pressure tests at a constant temperature in agreement with UNI EN 921 [15].

The main innovation of this work lies in the systematic experimental campaign that was performed to assess the effect of chlorine-based disinfectants on PE pipes. Both pipe samples and specimens were exposed in the plant to realistic conditions in order to reproduce the most critical environmental conditions occurring in real conveyance networks.

The results show that chlorine dioxide is much more aggressive on polyethylene than sodium hypochlorite. In the pipe itself, however, no significant decays of the mechanical and chemical properties were observed for either disinfectant. On the contrary, if exposed in the form of pre-cut dog-bone specimens, the material showed rapid decay of maximum elongation and antioxidant content when immersed in water treated with chlorine dioxide.

2. DESIGN OF EXPERIMENTS

An experimental approach was adopted to study the effect of chlorine on PE. The work started with the identification of all the factors involved in the interaction between disinfectant and polyethylene pipes (see Table 1) and the corresponding range of variability to be created in the test with the desired tolerance. The variables included the chemical, physical, structural, and geometrical aspects of the problem. The range of variability and tolerance for each variable were chosen in accordance with other authors [1, 2, 15] and on the basis of experimental feasibility.

One of the most important choices was how to expose the pipe. A critical investigation led to the implementation of a combined solution in the experimental plant (see Section 3) where both pipe sections and dog-bone specimens could be exposed simultaneously. The pipe sections reproduced the real exposure conditions, while the dog-bones allowed straightforward testing after exposure. The dog-bones were cut from the pipe wall with a cutting die aligned with the pipe axis. The dimensions of the coupons were in compliance with ISO 6259-1/3 [13-14]. Both sample types (pipe sections and dog-bones) were exposed to chlorinated and non-chlorinated water. An additional batch of pre-cut dog-bones was stored in the laboratory at the beginning of each test period to provide a neutral reference of material subject to minimal environmental exposure.

Table 2 presents the two main variables that are managed by the test plant and which varied over two levels. These variables included the free chlorine concentration and a miscellaneous variable. As described in Table 3, the miscellaneous variable combines the specimen type, the water speed, and the circumferential stress in the pipe wall. Each of these elementary variables is varied over two levels according to the type of exposure performed in the plant. The lower level of the miscellaneous variable corresponds to exposure in the tank, while the higher level to exposure in the form of pipe coils with water running inside.

The performance of the pipe sections and the dog-bone specimens tested in the plant were characterized chemically and mechanically. The chemical characterization was performed with an “Oxidation Induction Time” (OIT) test. The test quantified how many minutes the material took to oxidise. This then gave a measure of how much antioxidant was still available in the material.

The mechanical characterization consisted of a uniaxial monotonic tensile test performed on dog-bone coupons. Dog-bone specimens for the tensile test were also cut from the pipe sections exposed to running water. In addition, for the pipe exposed to chlorine dioxide, pressure tests at constant temperature were also performed in accordance with UNI EN 921 [15] and EN 12201-2 [16]. The purpose of this test was to establish a correlation between the outcome of the short-term tests (tensile and OIT) and the true long-term creep behaviour of the materials.

3. TEST PLANT

The experimental plant was specifically designed to carry out the full experimental plan described in the previous section efficiently and reliably. A structured design technique [17] was therefore adopted, consisting in the identification of the critical functions followed by the generation of the concepts that most convincingly embodied these functions. Figure 1 shows the overall plant layout obtained by combining the best concepts that emerged from the design process.

To evaluate the effects of disinfectant on material properties, two separate lines were created (A and B in Figure 1). Lines A and B form two identical testing environments, with the exception of the disinfectant concentration, which was kept at zero in one line (control line) and was set to the desired value in the other line (test line). Water heating was obtained through an independent line (C in Figure 1) where an electric boiler was installed. This line was equipped with two plate heat exchangers (HC in Figure 1) which supplied heat independently of each other, to the exposure lines A and B. The primary line of each heat exchanger can be circumvented through an automatically controlled by-pass line. Besides providing an accurate control of the temperature in each exposure line, this solution has two additional advantages. Firstly, it keeps the disinfectant out of the heating line. Secondly, it allows the heat to be delivered to different locations along the exposure lines or to achieve different temperatures in the two lines.

The pre-cut dog-bone specimens were placed in a thermally insulated tank, which was accessible from the top, and installed serially in each exposure line. The specimens were accommodated in a specific basket hung in the tank (Figure 2a), which allows the water to flow around the whole surface of the specimens. Due to the wide diameter of the tanks with respect to the cross section of the main lines, the water speed was almost zero in the tank volume. Specimens were inserted and extracted by opening the top of the tank, an operation that required less than thirty minutes to be performed. In the process, neither the plant nor the tank needed to be emptied out but only de-pressurized so that the extraction only minimally affected the chemical and physical parameters of the system. I am not sure about the tenses used here. Maybe the present is appropriate, but I suggest you check to see how other authors manage the same situation.

The pipe to be exposed to the water was inserted in the line in the form of an off-the-shelf multi-coiled section (Figure 2b). The coils were enclosed in a thermally-insulated wooden box, in order to keep both the water running in the pipe and the pipe wall itself at constant temperatures.

The main water supply to the plant provided a pressure of 3 bar in the lines, thus giving the possibility to avoid an independent pumping system. A pressure regulator

(PR in Figure 1), was installed at the inlet of each exposure line to maintain a constant pressure value.

An activated carbon filter was installed on the supply line of the plant to remove chlorine from the main water. This was done in order to ensure neutral water in the non-chlorinated control line and allow the desired chlorination to be performed in the test line. In the test line, the concentration of disinfectant was regulated by a metering pump, which injected liquid disinfectant and was operated by a controlling device that receives feedback from a “redox” and pH sensor. This kind of system automatically and accurately measures the level of free chlorine in water. The disinfectants investigated in this research were sodium hypochlorite and chlorine dioxide, the latter managed by a commercial device with a maximum capability of 5 g/hour. The pH level was also controlled on both lines by a metering pump, operated by a controlling device, which received feedback from a pH sensor and injected an acid or a base. Each line was equipped with a controllable waste valve, which permanently spills a ratio of flowing water, in order to get a a steady pH level and an accurate free chlorine concentration.

The whole plant was made with AISI 316 stainless steel, with the exception of a few bronze or brass components. All the joints were threaded. The plant was monitored using a PC that was equipped with ad hoc acquisition software, which stores the most significant working parameters and has an alarm if one of these parameters goes out of the defined range. Once the construction of the plant was complete, a trial phase was performed to calibrate the controlling parameters.

4. EXPERIMENTAL CAMPAIGN

The experimental campaign consisted of two systematic test campaigns performed using the exposure plant previously described. These experimental campaigns were aimed at analysing polyethylene pipes (PE100) for alimentary use, with a nominal diameter DN32 and nominal maximum pressure PN25. During each campaign the pipe was exposed both in coils and as pre-cut tensile specimens.

The water temperature in the test plant was set at 40°C on both lines. This value was chosen as a trade-off between the contrasting needs to speed up the decay process and reproduce the environmental conditions of typical field usage as closely as possible. The average pressure in the plant was 2.5 bar, giving a circumferential stress in the pipe wall of 1.2 MPa. The volumetric flow rate in the plant was approximately 2.7 m^3/h, resulting in a water speed of 1.78 m/s along the line. The pH level was kept at a constant value of 7.1, with an accuracy of 0.1, in both lines. Sodium hydroxide (NaOH) and nitric acid (HNO3), both available as 5% water solutions, were used to regulate the pH level for chlorine dioxide and sodium hypochlorite, respectively. In both experimental campaigns the volume of discharged water was 10 litres per hour (0.3% volumetric flow rate) in order to ensure that the water was restored correctly.

Each experimental campaign lasted one year and considered three different exposure conditions (both for the coiled pipes and the pre-cut dog-bones): neutral water, chlorinated water and ambient air. Exposure to neutral and chlorinated water was performed in the test plant. Exposure to air was performed by simply putting aside samples in different forms (see below). The first reason for this was to provide the reference characteristic of naturally aged pipes. The second was to monitor the effects on the measured tensile properties produced by the wear of the cutting die used to extract the dog-bone specimens from the pipe coils.

The whole batch of specimens, cut from the pipe before the tests began, was immersed into each tank. A pipe coil and dog-bone specimens, of the same length and in equal number as in the plant, were exposed to air. All the polyethylene tested in the two experimental campaigns came from the same 100 m long coil.

4.1. Experimental campaign on chlorine dioxide

The first experimental campaign investigated the effect of chlorine dioxide disinfectant at a constant concentration of 5 ppm in order to obtain a free chlorine concentration of approximately 2.5 ppm.

The campaign lasted one year. In the first two months, samples were extracted from the plant once a week, then every two weeks until the end of the year of testing. Six sets of specimens were collected from each extraction according to the pattern shown in Figure 3. Three pre-cut dog-bones were extracted from the non-chlorinated tank (white specimens, WS); three pre-cut dog-bones were extracted from the chlorinated tank (chlorinated specimens, CS); three pre-cut dog-bones were extracted from the batch exposed to air (reference specimens, RS); four dog-bones were cut (see below) from a pipe section extracted from the non-chlorinated line (white pipe, WP); similarly, four dog-bones were cut from a pipe section extracted from the chlorinated line (chlorinated pipe, CP); finally, four dog-bones were cut from a pipe section extracted from the coil exposed to air (reference pipe, RP). The pipe sections collected from the coils were approximately 30 cm long. Each pipe section was split into four parts by cutting the sample along a longitudinal and a transverse symmetry plane. From each resulting part a dog-bone (conforming to ISO 6259-3) was obtained by means of the cutting die.

4.2. Experimental campaign on sodium hypochlorite

The second experimental campaign investigated the effect of sodium hypochlorite disinfectant at a constant concentration of 2.5 ppm (with the same concentration of free chlorine). All the dog-bone specimens processed in the test campaign were obtained with the same procedure described for the experimental campaign on sodium hypochlorite (Section 4.1).

This campaign also lasted for one year. Based on experience from the previous campaign, the sample extractions were scheduled every three days for the first three times, once a week for the next three times, then every two weeks for three times and finally every two months until the end of the year. The specimens were classified according to type (pre-cut dog-bones or pipe sections) and exposure (non chlorinated water, chlorinated water and air) again using the code in Figure 3. In this second campaign, six replicates were performed for each test condition in order to reduce the scatter affecting the measurements for three/four specimens in the previous campaign.

4.3 Mechanical and chemical characterization

A mechanical and a chemical characterization were carried out on the specimens extracted. The mechanical characterization was performed through monotonic tensile tests up to failure, and pressure tests at a constant temperature. The chemical characterization consisted of OIT tests carried out on the RS, WS, CS, WP, CP (Figure 3) specimens by performing three replicates. The samples for the OIT tests were obtained by trimming a cylindrical specimen with a 6 mm diameter with a sharp tool, from one head of the dog-bone specimen used in the subsequent monotonic tensile test. Two slices were then isolated and tested from each sample, one slice extracted from the internal surface of the pipe and the other from the midlayer. The test was performed with a differential calorimeter at a temperature of 210°C in an oxygen atmosphere.

The monotonic tensile tests were carried out on an electromechanical testing machine (Galdabini SUN 500) with a load capacity of 5 kN. The machine operation was controlled by a PC, equipped with proprietary data acquisition software. The test conditions adopted (similar to ISO 6259-1/3) matched those investigated in a previous work by the authors [18] where a particularly robust set of parameters was found. The test speed was set to 50 mm/min. In contrast with the standard, the elongation of the specimen was measured indirectly on the basis of the displacement of the moving crosshead. Since the deformation of the heads of the specimens was minimal, this was considered to have had a modest effect on the quality of the results. From the monotonic tensile tests, the following features of the stress-strain curve were recorded: yield strength (S_Y), ultimate tensile strength (S_u), percent elongation at fracture (ε_F), and elastic modulus (E).

As a further mechanical characterization, pressure tests at a constant temperature were performed on pipe samples from the campaign on chlorine dioxide. A pipe sample (approximately one meter long) from each of the batches RP, WP and CP was tested. The tests were performed by the Italian Plastic Institute according to UNI EN 921 [15]. The pipe samples were subjected to an internal pressure generating a circumferential stress of 5 MPa (for PE 100) in the pipe wall at a constant temperature of 80°C. Three time periods were examined in the test: 165, 1000 and 2000 hours.

5. RESULTS

This section presents the results of both experimental campaigns performed on the test plant. The results regard the mechanical and chemical characterization performed on the specimens that were sampled during the exposure. A comparison between the two types of disinfectant is also provided.

Figure 4 presents the mean value of percentage elongation at failure, ε_f, as a function of time (days). The results are displayed for all the experimental conditions (Figure 3) both for the campaign investigating the effect of chlorine dioxide (Figure 4a) and for on sodium hypochlorite (Figure 4b).

The diagrams in Figures 5 and 6 display the OIT as a function of time (days) at the inner surface (Figure 5) and at the mid layer of the pipe wall (Figure 6). These diagrams refer both to chlorine dioxide (Figures 5a and 6a) and to sodium hypochlorite (Figures 5b and 6b).

Figure 7 shows the typical texture of the inner surface of the specimens after the tensile tests, highlighting the difference between those exposed to chlorine dioxide (Figure 7a), those exposed to non-chlorinated water (Figure 7b), and those exposed to sodium hypochlorite (Figure 7c).

The bar chart in Figure 8 compares the effects of chlorine dioxide and sodium hypochlorite on the elongation at failure and OIT (the latter measured both at the mid layer and inner surface). The results refer to the last sampling of the experimental campaigns and are provided in terms of average values.

Table 4 summarizes the results of the pressure tests at a constant temperature of 80°C performed by the Italian Plastic Institute. The tests were performed on three pipe samples exposed in the chlorine dioxide campaign for each of the batches RP, WP and CP. In all the tests no failures were observed on the pipe samples at the end of the test period (2000 hours).

6. DISCUSSION

The diagrams in Figure 4 show a strong instability of the elongation at failure, ε_f, in both the experimental campaigns. Also the scatter of results at each sampling (not reported here for clarity) was quite high. The greatest reduction of the elongation at failure is observed for the CS specimens exposed to chlorine dioxide (Figure 4a). From the second week of testing, a decrease of 90% was recorded, which remained almost constant for the rest of the test period. This drastic reduction could be attributed to the severe exposure conditions of these specimens, which were fully immersed and exposed to the chlorine effect on both inner, outer and side surfaces. After an initial phase of high instability, RP, WP, and CP specimens also exhibited a decrease of about 50% in the elongation at failure, in particular at the end of the test campaign.

Since this decrease was almost the same both for the RP and the WP and CP specimens, it must be due to the consumption of the cutting die. In contrast, exposure to chlorinated or non-chlorinated water did not show any significant effect.

Finally, the response of RS specimens in terms of elongation at failure throughout the test campaign was quite similar to the WS specimens (Figure 4a). However, at the end of the test campaign, the WS specimens showed a lower and more unstable response than the reference batch (RS). This could be attributed to the combined effects of water and temperature.

A quite different behaviour, in contrast, can be observed in Figure 4b for sodium hypochlorite, which did not produce a significant decrease in elongation at the failure of any of the specimens. Their response became almost steady towards the end of the test campaign, without significant differences between the batches.

In Figure 5, a similar behaviour to the elongation at failure can be observed for the OIT as a function of time. Both CS and CP specimens present a noticeable decrease in the OIT, at their inner surface. In the case of exposure to chlorine dioxide (Figure 5a) both CS and CP specimens highlight an abrupt decrease of the OIT from the second week of test. The OIT value then became stable at 90% less than its initial value from the second month of exposure until the end of the test campaign.

A similar trend can be observed for the CS and CP specimens exposed to sodium hypochlorite (Figure 5b) where a monotonic decrease in the OIT value up to 60% affects the last samplings. The other batches (RS, WS and WP) also showed a decay of the OIT, in particular in the first experimental campaign (Figure 5a). Here a maximum reduction of 30% was observed. By comparison, in the second test campaign (Figure 5b) the specimens aged in air (RS) provided quite constant OIT values. In contrast a slight decrease, up to a maximum of 20%, can be observed in the WS and WP specimens.

Two conclusions can be drawn from these results. Firstly, both dog-bone specimens and pipe samples are equally subject to antioxidant consumption on their inner surface. Secondly, a natural consumption of antioxidants occurs even for dog-bone specimens and pipe exposed to ambient air or to non-chlorinated water.

Figure 6 clarifies that the decrease in the OIT on the mid layer of the pipe wall is quite low for exposure both to chlorine dioxide (Figure 6a) and to sodium hypochlorite (Figure 6b). A somewhat different behaviour can be observed for the CP and CS specimens exposed to chlorine dioxide (Figure 6a), with the CP specimens showing a slight reduction and the CS specimens exhibiting a marked decrease in OIT.

On the whole, the results demonstrate that chlorine dioxide is more aggressive on polyethylene than sodium hypochlorite. This conclusion holds true both in terms of elongation at failure (Figure 4) and in terms of antioxidant consumption (Figures 5-6). In addition, the differences between the disinfectants can also be seen from the different appearance of the specimen surfaces after the tensile test, as shown in Figure 7.

Figure 7a presents a specimen obtained from the pipe exposed to chlorine dioxide, Figure 7b from the pipe exposed to neutral water, and Figure 7c from the pipe exposed to sodium hypochlorite. In Figures 7a and c the surfaces appear quite rough, thus highlighting the detrimental effect of chlorine on polyethylene. However, the highest degradation of the surfaces was observed on the specimen in Figure 7a, which was exposed to chlorine dioxide.

In both experimental campaigns, the degradation, either mechanical or chemical, is more significant on the pre-cut dog-bone specimens, which appear more vulnerable than the pipe sections from which the dog-bones were extracted after exposure. The higher degradation of the pre-cut dog-bone specimens is probably due to their direct exposure to chlorine dioxide through the lateral surface originated by the cutting die. The higher mechanical performance of the pipe could thus be attributed to a protective layer formed at the inner surface of the pipe during manufacture (extrusion). This protective layer shields the inner material from the direct aggression of the chlorine. However this hypothesis needs further investigations to be assessed more clearly.

One conclusion that can be drawn by comparing Figure 4 with Figures 5 and 6 is that a high degree of antioxidant consumption (see for example, specimens CS and CP exposed to chlorine dioxide) does not necessarily imply a decrease in the elongation at failure. Furthermore, the bar chart in Figure 8 emphasizes that, at the end of the experimental campaign, the specimens exposed to chlorine dioxide exhibited lower elongation at failure and OIT values than those specimens exposed to sodium hypochlorite.

Table 4 confirms that the mechanical properties of the polyethylene pipe were not affected by the exposure to chlorine dioxide. All the pipe samples (exposed to air (RP), to neutral water (WP) or to chlorine dioxide (CP)) survived the pressure tests at a constant temperature for up to 2000 hours.

CONCLUSIONS

The effect of disinfectants on high-density polyethylene (HDPE) pipes, commonly used in modern urban networks for water conveyance, has been examined experimentally. Two systematic test campaigns were performed using a specifically built test plant. The first campaign investigated the effect of chlorine dioxide at a constant concentration of 5 ppm, the second investigated the effect of sodium hypochlorite at a constant concentration of 2.5 ppm. These different concentrations of disinfectants were chosen so as to produce the same concentration (5 ppm) of free chlorine in the exposure line. The test campaigns involved PE100 pipes for alimentary use with a nominal diameter DN 32. The pipes were exposed both in the form of pre-cut dog-bones immersed in still water and as pipe sections exposed to running water. Chlorine dioxide appeared to be the most aggressive disinfectant since it led to a drastic reduction in elongation at failure of the pre-cut dog-bone specimens, together with a dramatic antioxidant consumption after a few weeks of exposure. In contrast in the case of sodium hypochlorite, the monotonic tensile tests up to failure highlighted no substantial influence on the mechanical behaviour of PE. This is in accordance with the slight antioxidant consumption testified by the OIT tests.

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FIGURE CAPTIONS

Figure 1 Functional layout of the plant

Figure 2 Type of specimens exposed in the plant during the experimental campaign: dog-bone specimens in the basket to be placed in the tank (a) and pipe coil in the hang (b)

Figure 3 View of the test plant illustrating the exposure of pre-cut dog-bones and pipe sections and the extraction of dog-bones from pipe sections

Figure 4 Percentage elongation at failure, ε_f, vs exposure day for chlorine dioxide (a) and sodium hypochlorite (b)

Figure 5 OIT vs days at inner surface for chlorine dioxide (a) and sodium hypochlorite (b)

Figure 6 OIT vs days at mid-layer for chlorine dioxide (a) and sodium hypochlorite (b)

Figure 7 Detail of specimens exposed to chlorine dioxide (a) neutral water (b) and sodium hypochlorite (c)

Figure 8 Bar chart of comparison between the experimental test campaigns

Table 1 Variables

Table 2 Variables managed by the plant

Table 3 Variables that constitute miscellaneous variables

Table 4 Results of the pressure tests at a constant temperature of 80°C on specimens exposed to chlorine dioxide

Table 1

Variables	Unit	Min	Max	Tolerance
Free chlorine concentration	ppm	0	5	±0.1
Water temperature	°C	25	80	±0.1
Water pressure	Bar	0	3	±0.2
Circumferential stress	MPa	0	1.5	±0.1
Water speed	m/s	0	3	±0.1
Disinfectant type	Categorical	ClO_2	NaClO	--
Water pH	--	6.5	7.5	±0.1
Pipe diameter	mm	32	50	±2
Exposure time	days	0	365	±1

Table 2

Variables	Levels	
Free chlorine concentration (ppm)	0	2.5
Miscellaneous variable	low	high

Table 3

	Levels	
Variables	**Low**	**High**
Specimen	Dog-bone	Pipe sample
Water speed (m/s)	~0	2.5
Circumferential stress (MPa)	0	1.5

Table 4

	Time (h)		
	165	1000	2000
RP 1	passed	passed	passed
RP 2	passed	passed	passed
WP 1	passed	passed	passed
WP 2	passed	passed	passed
CP 1	passed	passed	passed
CP 2	passed	passed	passed

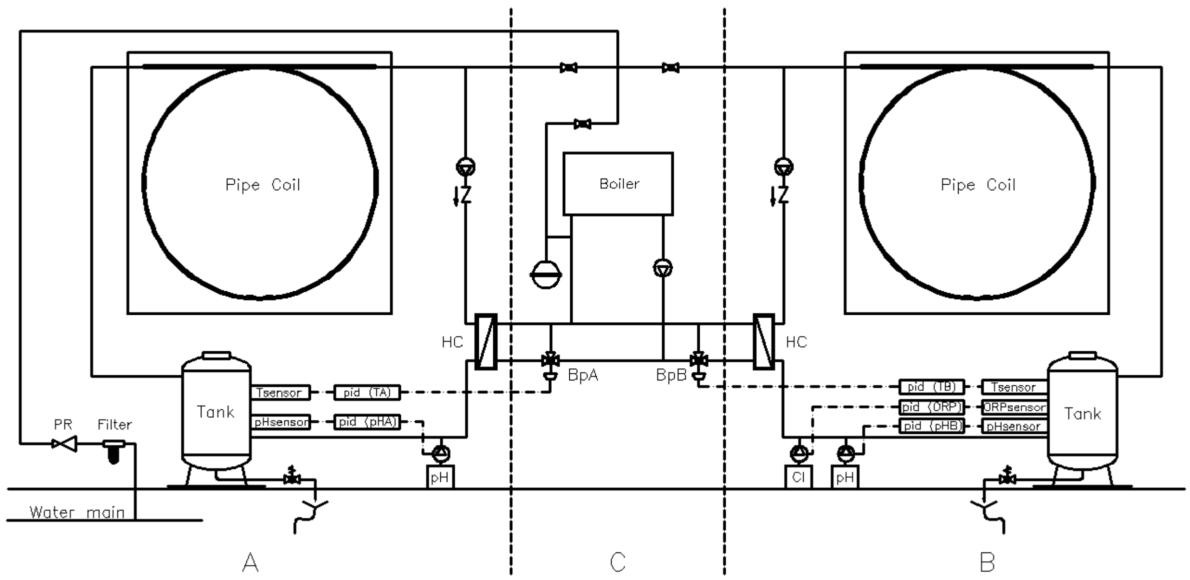

Pipe Coil
Boiler
Pipe Coil
HC
BpA
BpB
HC
Tank
Tsensor
pid (TA)
pHsensor
pid (pHA)
PR
Filter
pH
Water main
pid (TB)
Tsensor
pid (ORP)
ORPsensor
pid (pHB)
pHsensor
Tank
Cl
pH
A
C
B

Figure 1

(a)

(b)

Figure 2

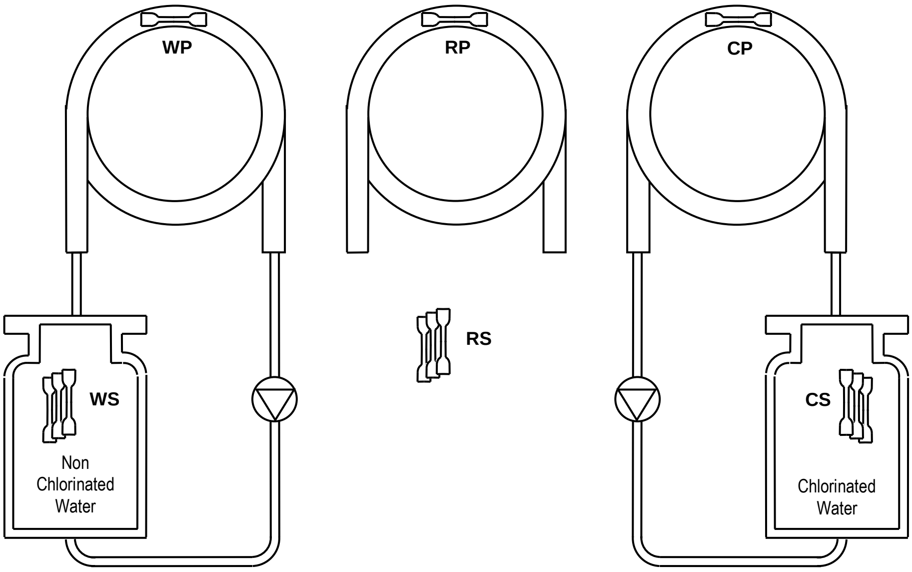
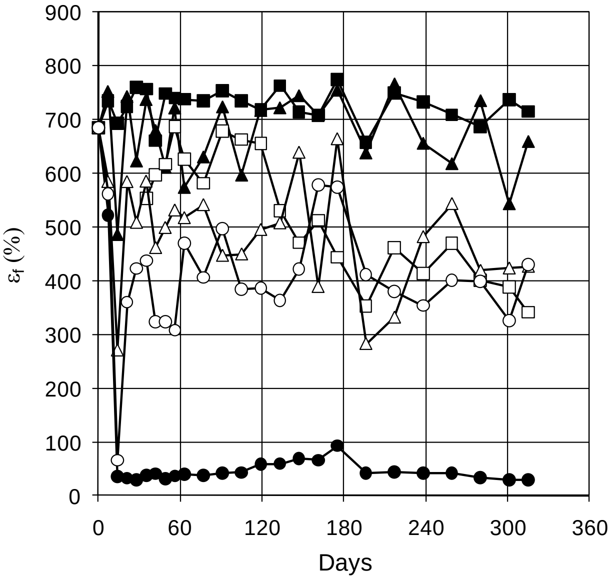
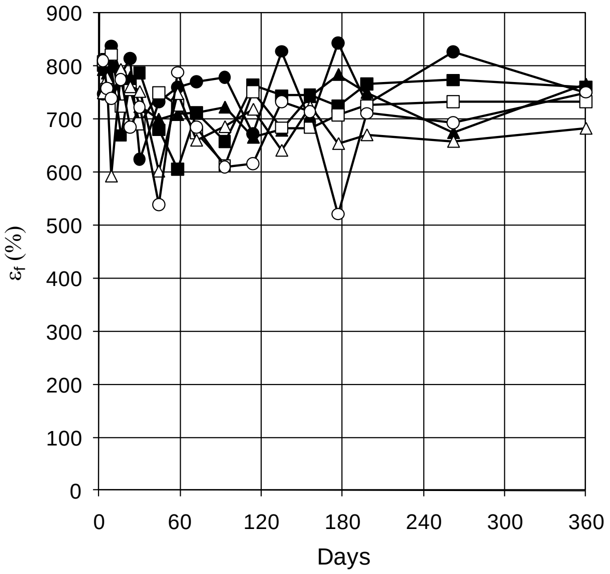


Figure 3


900
800
700
600
500
400
300
200
100
0
ε_f (%)
0
60
120
180
240
300
360
Days

(a)


900
800
700
600
500
400
300
200
100
0
ε_f (%)
0
60
120
180
240
300
360
Days

(b)


RS
WS
CS
RP
WP
CP

Figure 4

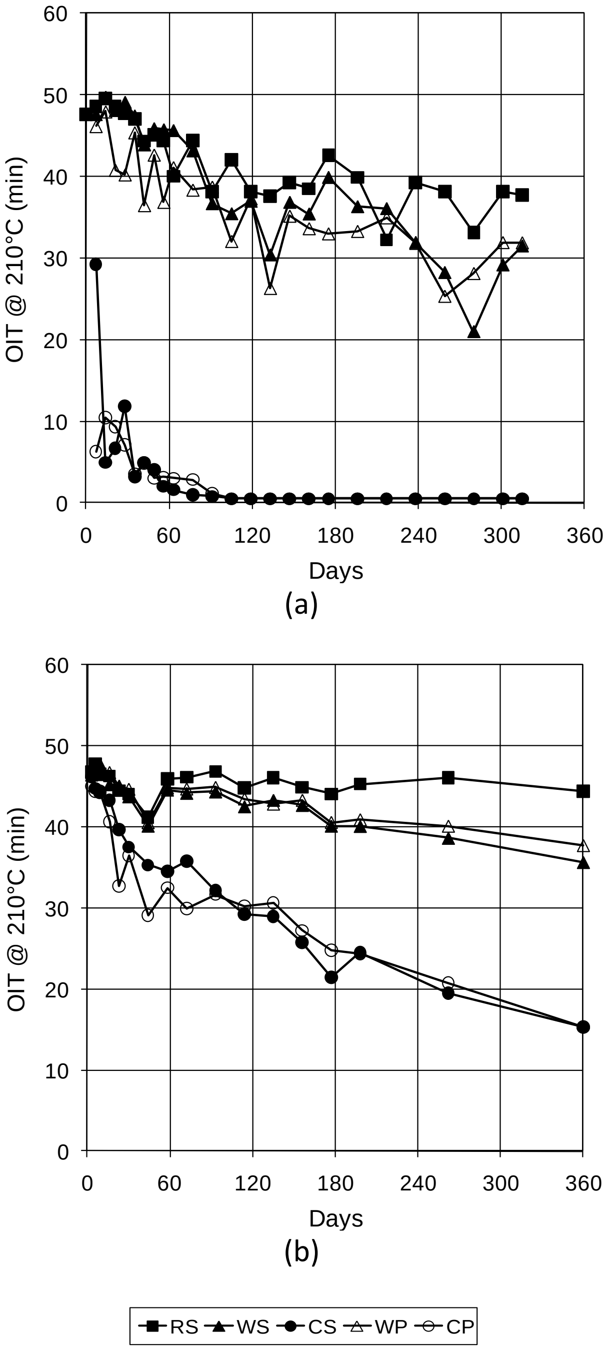


Figure 5

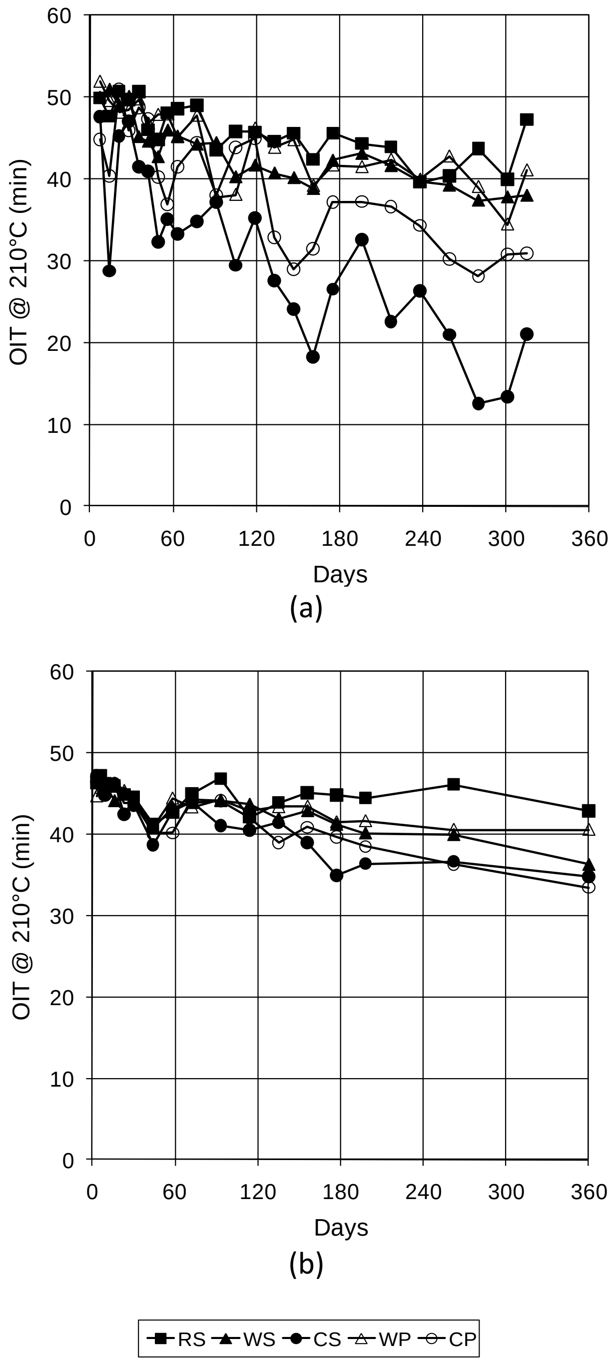
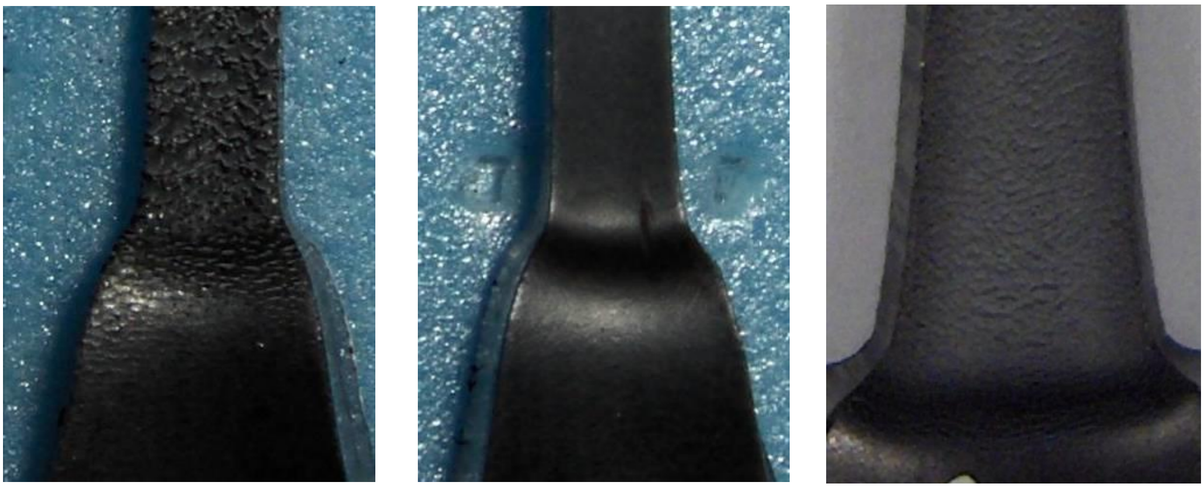

60
50
40
30
20
10
0
OIT @ 210°C (min)
0
60
120
180
240
300
360
Days
(a)
60
50
40
30
20
10
0
OIT @ 210°C (min)
0
60
120
180
240
300
360
Days
(b)
RS
WS
CS
WP
CP

Figure 6



(a) (b) (c)

Figure 7

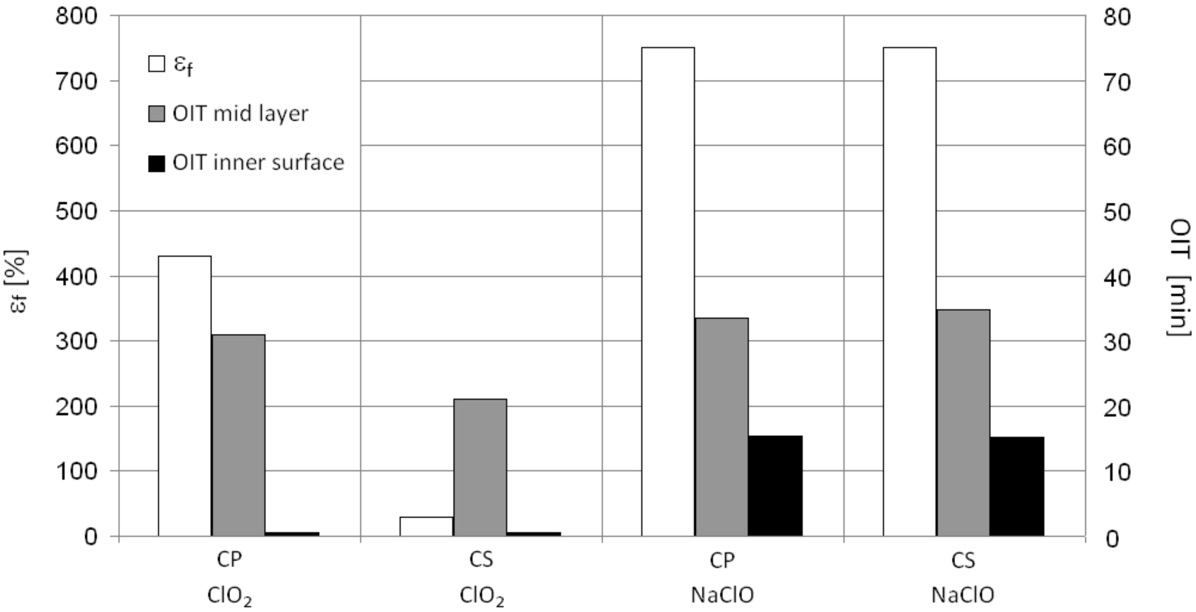


Figure 8