Pergamon

Cement and Concrete Research 31 (2001) 543–553

CEMENT AND CONCRETE RESEARCH

The durability of cellulose fibre reinforced concrete pipes in sewage applications

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Received 20 January 2000; accepted 13 October 2000

Abstract

Concrete pipes are integral components of the community's infrastructure, being employed in a wide range of applications from storm-water drainage to external casing for composite piles. Their use as sewage pipes requires consideration of both the strength characteristics and the long-term durability of the pipes in aggressive environments. Cellulose fibre reinforced concrete (FRC) pipes are relatively new to the market and if they are to find a place in the sewage pipe market, then their long-term durability in a sewage environment must be investigated. This paper presents the preliminary findings of a research program aimed at determining the long-term durability of FRC pipes in sewage applications. Pipe samples of both FRC and steel reinforced concrete (SRC) were exposed to sewage environments and the characteristics of the samples continually monitored. It was found that the strength characteristics of the samples were only slightly affected by the environment but that the surface characteristics of the materials changed significantly.

Keywords: Durability; Fibre reinforcement; SEM; Degradation; Cellulose fibres

1. Introduction

Concrete pipes have long been considered as integral components of our infrastructure. This may be attributed to the diversity of their application and perceived excellent durability. One of the main uses for concrete pipes is in the transportation of sewage, a role in which they have been employed since Roman times [1]. Today, in Australia and throughout the world, concrete pipes are still employed in this role with the vast majority in good condition, showing negligible signs of deterioration often after more than 50 years in operation [1].

In comparison, cellulose fibre reinforced concrete (FRC) pipes are a relatively new product, introduced to the concrete pipe market in 1986 as a replacement for the previously popular asbestos cement pipe material. To date, these pipes have not been utilised in sewage transport applications. With the strength characteristics of this material well-documented [2], potential for employment in sewage reticulation will be dependent on the long-term durability of the pipe material in what is potentially a hostile environment.

2. Cellulose FRC pipes

Cellulose FRC is essentially an autoclaved concrete (fine aggregate) matrix reinforced with cellulose fibres. This material is produced in the form of pipes at only one place worldwide, at the James Hardie Meeandah Plant located in Brisbane, Australia. The company is presently expanding its activities into North American markets and FRC pipes could soon appear in the USA.

FRC pipes are manufactured by means of the Mazza process [2]. Initially, a blend of Portland cement, silica (in the form of ground sand), cellulose fibres and an aluminium catalyst (James Hardie and Coy, unpublished work) is thoroughly mixed into a thin slurry of approximately 10% solids and 90% water. This mix is then spread into a thin, continuous layer, which proceeds through a vacuum de-watering process before being laminated and compressed onto mandrels to form pipes of the desired dimensions. After an initial presteaming phase, the mandrels are removed and

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0008-8846/00/$ – see front matter
PII: S0008-8846(00)00451-8

the pipes are cured at high temperature and pressure in an autoclave. This process of manufacturing results in a composite with unique characteristics; characteristics imparted by both the component materials (the autoclaved concrete matrix and the cellulose reinforcing fibres) and the nature of their interface.

3. Utilising FRC pipes in sewage applications

Concrete sewage pipelines have a long history of excellent durability, and it is expected that FRC pipes will also perform well. In many ways, buried pipelines are ideally placed to ensure their longevity. Soil moisture ensures continued curing and strength gain, temperatures are relatively constant minimising thermal stresses, and in most cases, drying shrinkage does not take place. For the majority of applications, the soils in which the pipes are buried are not aggressive to concrete [3]. Thus, the long-term durability of FRC pipes utilised in sewage systems will normally be solely a function of the sewage effluent.

3.1. The aggressive nature of sewage effluent

Domestic sewage is alkaline in nature and is usually harmless to concrete pipes [4]. In some situations, a sewage system may carry industrial or trade waste that is high in acids or organic chemicals. Although rare, in these situations, the sewage may prove detrimental to the long-term performance of the pipeline. The greatest potential problem for sewer pipes, however, is corrosion caused by bacteria. The metabolic activity of many bacteria forms acids that may attack concrete [5], the most harmful of which are the bacteriological processes associated with the generation of hydrogen sulphide within the pipes. Of the small proportion of concrete sewage systems that have failed in recent years, this form of internal corrosion accounts for almost all of the failures [1].

The generation of hydrogen sulphide gas within sewage pipes is brought about by a unique set of conditions. If the flow of sewage in the pipe is sluggish, and especially if the temperature is relatively high and the sewage is strong (high BOD, high organic content), it may be expected that sulphide concentrations will build up downstream within the pipe [6]. Hydrogen sulphide may then be produced by the reduction of these sulphides by anaerobic bacteria present within the slime growth below the waterline [1]. If somewhere downstream in the pipe the sewage effluent becomes fast moving and turbulent, the dissolved hydrogen sulphide may be released as a gas into the void above the flow level of the sewage.

While the liberation of this highly toxic and odourous gas in sewers is unfavourable for a number of reasons, hydrogen sulphide is actually relatively harmless to concrete. Rather it is the oxidisation of this compound that proves detrimental to the performance of concrete sewers. Aerobic bacteria present in the moisture, which lines the pipe above the level of sewage flow, may readily oxidise hydrogen sulphide to form concentrated sulphuric acid [3]. It is this sulphuric acid, intensified at the waterline, that may prove detrimental to the performance of sewage pipelines.

3.2. The effects of sulphuric acid on FRC

As previously discussed, FRC is a composite material consisting of cellulose reinforcing fibres within an autoclaved concrete matrix. Utilised as sewage pipelines, the production of concentrated sulphuric acid may readily degrade both of these component materials. The attack is concentrated around the waterline indicating that this is where the oxidation of hydrogen sulphide takes place.

Concrete is an alkaline material that will be readily attacked by sulphuric acid, attack occurring at values of pH below about 6.5. The free hydrogen ions associated with the acid serve to accelerate the leaching of calcium hydroxide and may also attack the C-S-H gel to produce silica gel [5]. Although the crystalline structure of FRC may be expected to resist deterioration by sulphuric acid better than conventional concretes, the ultimate effect of such attack will be the transformation of good concrete sewer pipes to a soft and mushy mass [4].

Similarly, cellulose fibres are also susceptible to attack by sulphuric acid, although the concrete matrix in which they are embedded will limit the access of the acid to the fibres. Assuming that the permeability of the concrete matrix renders the fibres accessible, the sulphuric acid (which is not a solvent for cellulose) will only penetrate the amorphous regions of the fibres resulting in heterogeneous deterioration [7]. In this type of degradation, cellulose fibres maintain their fibrous nature to a certain degree but will display a progressive loss of fibre strength. If carried to completion, this deterioration process would ultimately progress to a complete loss of fibre structure as the cellulose micro-fibrils are broken down into glucose molecules [8]. However, it is not considered that this level of fibre degradation represents a threat to the performance of the FRC pipes, as the integrity of the concrete matrix would be jeopardised long before this extent of fibre degradation occurs.

3.3. Biological degradation of the fibres

While acidic degradation of sewage pipelines has been the primary cause of failure in traditional concrete pipe sewers, the possibility of failure of FRC pipes due to the biological deterioration of the reinforcing fibres must not be overlooked. Biological degradation, also known as enzymatic degradation, of cellulose is the most common form of cellulolytic decomposition. As a consequence, this form of degradation can pose a significant threat to the satisfactory performance of FRC pipes in sewage applications.

As with all biota where cellulosic waste accumulates, sewage is a known source of cellulolytic micro-organisms, dominantly bacteria and fungi [9]. It is an anaerobic media of mixed populations comprising cellulolytic and noncellulolytic species that often interact to attack the cellulose fibres. This biodegradation, brought about by the action of enzymes known as cellulases, is similar in nature to acidic attack [10]. The consequence of this attack is a significant loss of strength within the cellulose fibres, and in extreme cases, the complete degradation of cellulose to carbon dioxide, methane and water [11].

Although environmental factors greatly influence the rate at which this process may proceed, accessibility remains the key to enzymatic degradation [12]. If the fibres are inaccessible to cellulolytic micro-organisms, or if the by-products of degradation cannot escape, then decomposition of the cellulose fibres will be minimised. In this respect, the concrete matrix within FRC will dictate the extent to which biological degradation of the reinforcing fibres is possible. In other words, if the concrete matrix can itself resist deterioration, and is not sufficiently permeable so as to leave the fibres exposed to cellulolytic microorganisms, then the threat of cellulolytic decomposition of the reinforcing fibres jeopardising the integrity of the pipes is negligible.

4. Experimental program

The research program was focused on monitoring the changing material properties of FRC pipes when exposed to aggressive situations that generally simulated the deterioration mechanisms experienced in the transportation of sewage effluent. As outlined earlier, the deterioration of these pipes when utilised in sewage systems may be attributed to either acid attack, arising from the production of hydrogen sulphide in the pipeline, or biological degradation of the reinforcing fibres by the sewage itself. Consequently, the study described has focused on modeling these two forms of attack in a controlled and accelerated fashion.

4.1. Materials and samples

The study focused on variations in the material properties of the FRC composite including surface dry mass, wall thickness and pipe strength. Accordingly, each sample set consisted of the following specimens:

- Eight coupons of FRC pipe material for accelerated testing aimed at monitoring the rate of change in surface dry mass and wall thickness of the material over time.
- Eight coupons of steel reinforced concrete (SRC) pipe material were included to provide a reference gauge for the observed changes in the FRC pipe material.
- Twenty-eight 100-mm annular sections of FRC pipe for monitoring variations in the strength characteristics of the pipes over time.

4.2. Test environments

As previously stated, the mechanisms for degradation of FRC pipes employed in sewage applications are limited to attack of the matrix or fibres by sulphuric acid, or the biological degradation of the fibres. Consequently, three testing environments were selected for this research program.

4.2.1. The Gibson Island Waste Water Treatment Plant (aerobic biodegradation)

This plant treats both industrial and domestic sewage produced within a catchment area stretching from the Murrarie to Calamvale areas of Brisbane. A sample set was fully submersed in the extended aeration tanks of this facility. The effluent in this component of the plant is essentially screened sewage mixed with ‘activated sludge.’ Within the extended aeration tanks, this sewage and sludge biomass is aerated to create an environment of micro-organisms, which will absorb and ingest the organic matter present in the sewage effluent. While not truly representative of the biological environment present within a sewer, the environment prevalent within these tanks does represent an extreme situation with respect to the aerobic biodegradation of the fibres. This test environment was included to determine the extent to which the alkalinity and permeability of the concrete matrix would protect the cellulose fibres from decomposition by cellulolytic micro-organisms.

4.2.2. Suncoast Waste Water Treatment Facility (anaerobic degradation)

This wastewater treatment facility, located at Bli-Bli on the Sunshine Coast, is a very small facility when compared with Gibson Island. It treats only the domestic waste produced within the Bli-Bli catchment area. Within this facility, a sample set was placed in the anaerobic portion of the oxidation ditches. Following screening and treatment in the aerobic portion of the oxidation ditches, sewage effluent enters the nonaerated section of the ditches. Within this section of the sewage treatment process, anaerobic bacteria reduce the nitrates present in the effluent to nitrogen gas, which escapes into the atmosphere. Since the raw sewage effluent transported by pipes is known to be an anaerobic biomass of cellulolytic micro-organisms, this test environment was selected to model the effects of anaerobic degradation of the fibres as represented within a sewer.

4.2.3. Sulphuric acid testing at QUT

The effects of sulphuric acid degradation were investigated using a large recycling acid bath maintained at a pH of about 5. Actual pH varied between 4.8 and 5.5 due to the amount of acid necessary for the complex dosing and mixing system required for the large volume of acid within the bath. Although the acid was not highly concentrated, the in situ degradation mechanisms were obtained for investigation. While there is a potentially large differential between the simulated acid environment of pH 5 and the possible pH 1 to pH 3 obtained in sewers, the attack mechanism remains constant. The pH 5 environment employed within this study was intended to provide an indication of the relative performance of FRC and SRC pipes exposed to acidic attack.

In addition to these aggressive test environments, a fourth sample set was placed in water for the duration of the testing. It is known that both moisture content and age affect the material characteristics of FRC [2]. Consequently, the fourth sample set was included as a control, providing baseline data on the general performance of FRC over the duration of testing.

4.3. Testing procedure

In order to monitor the surface characteristics of FRC pipes, coupon samples of FRC and SRC were placed in stainless steel cages and exposed to the test environments detailed. Each month these samples were retrieved for the purposes of visual observation and measurement of the wall thickness and surface dry saturated mass. Prior to their replacement in the test environment, each specimen was scrubbed to remove any loose products of degradation or nonreactive by-products present on the sample surface. This process was adopted based on the findings of a series of earlier pilot studies. These pilot studies found that once degradation of the FRC composite is initiated, the rate at which this degradation progresses is significantly slowed by the presence of the affected layer at the surface of the sample. The action of regularly scrubbing the samples removes this affected layer and serves to accelerate the process of degradation.

The strength characteristics of FRC pipes were monitored through the load testing of pipe sections. Every 3 months, three annular sections of FRC were removed from the various testing environments and loaded to failure under the action of an externally applied compressive load, using a three-line load configuration. Coupled with three-point flexure testing of the broken sections of the ring, variations in strength, including the maximum tensile (bending) capacity, of the exposed pipe sections were monitored.

Scanning electron microscopy (SEM) utilising a field emission electron microscope fitted with an energy dispersive X-ray analyser was used to investigate the surface of both the scrubbed FRC coupons and unscrubbed pipe sections at six monthly intervals. In this regard, the FRC degradation mechanisms associated with each of the test environments could be identified.

5. Results

Analysis of the wall thickness and saturated, surface dry mass of the coupon samples provides an indication of the changes occurring on the surface of these samples. Figs. 1

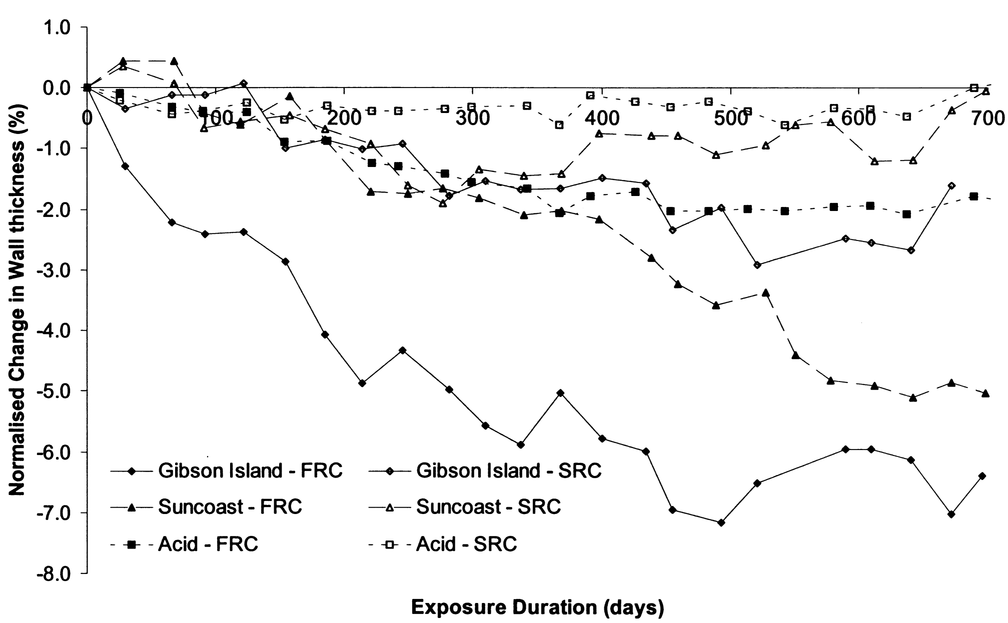

Fig. 1. Change in mid span wall thickness for FRC and SRC coupon samples.

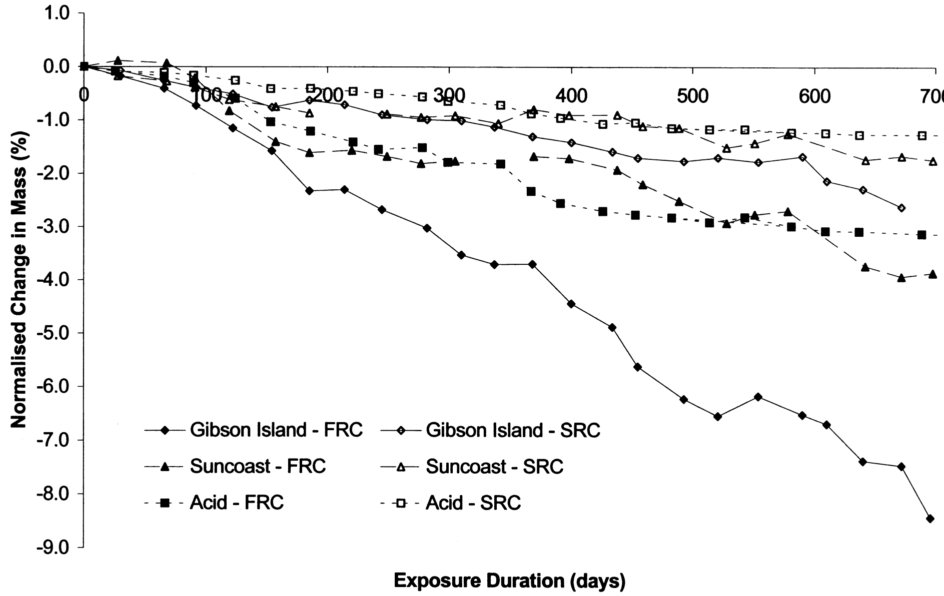

Fig. 2. Change in mass for FRC and SRC coupon samples.

and 2 show the average percentage change in these material properties, respectively. The data displayed in these figures is the difference between the measured changes in the test environment and the baseline data obtained from the control environment. In adopting this process of normalisation, the effects of the exposure environments can be isolated from the general changes that occur in the FRC composite due to age and moisture content.

It should be noted that variability in observed data for all exposure sites, including the control, was typically in the order of 1% for measurement of mid span wall thickness and 0.5% for measurement of saturated surface dry mass. Thus, any trends observed in the data must take account of this observed variability.

The results of testing aimed at monitoring the strength characteristics of FRC pipe samples over time for each of the test environments are displayed in Figs. 3 and 4. These graphs show the average maximum load and maximum tensile capacity of the annular FRC sections for each of the test environments, including the control environment, at three monthly intervals throughout the exposure duration.

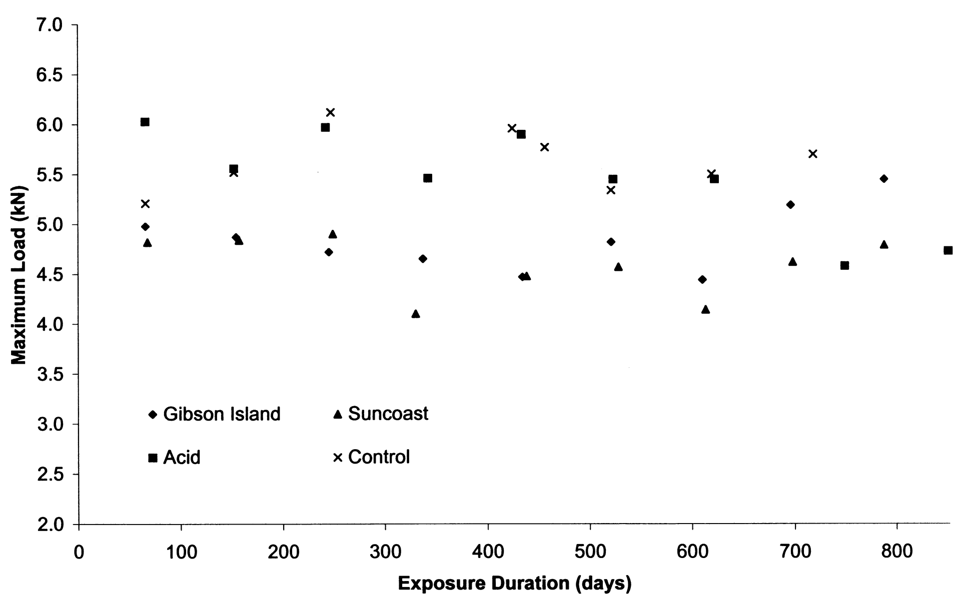

Fig. 3. Change in maximum load of FRC pipe sections.

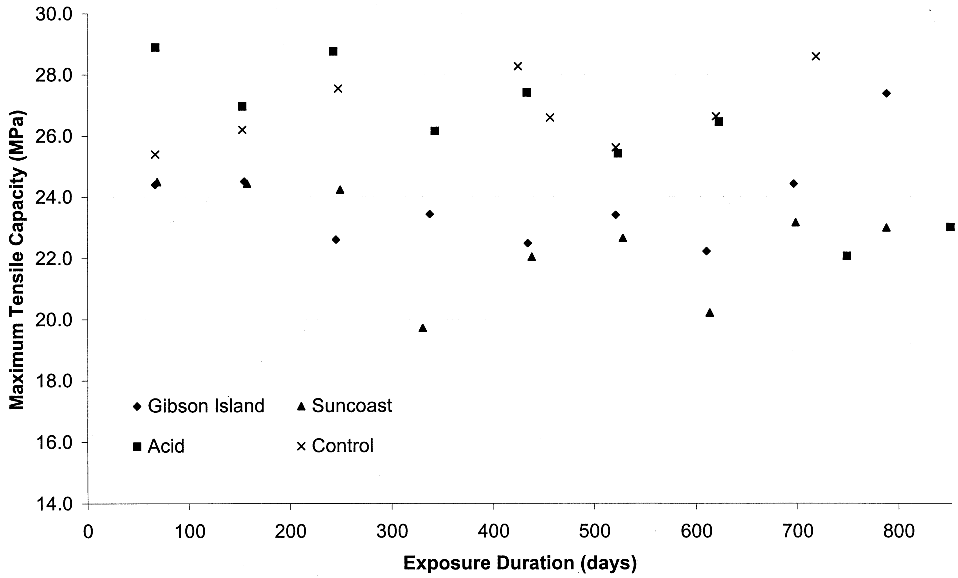

Fig. 4. Change in maximum tensile capacity of FRC pipe sections.

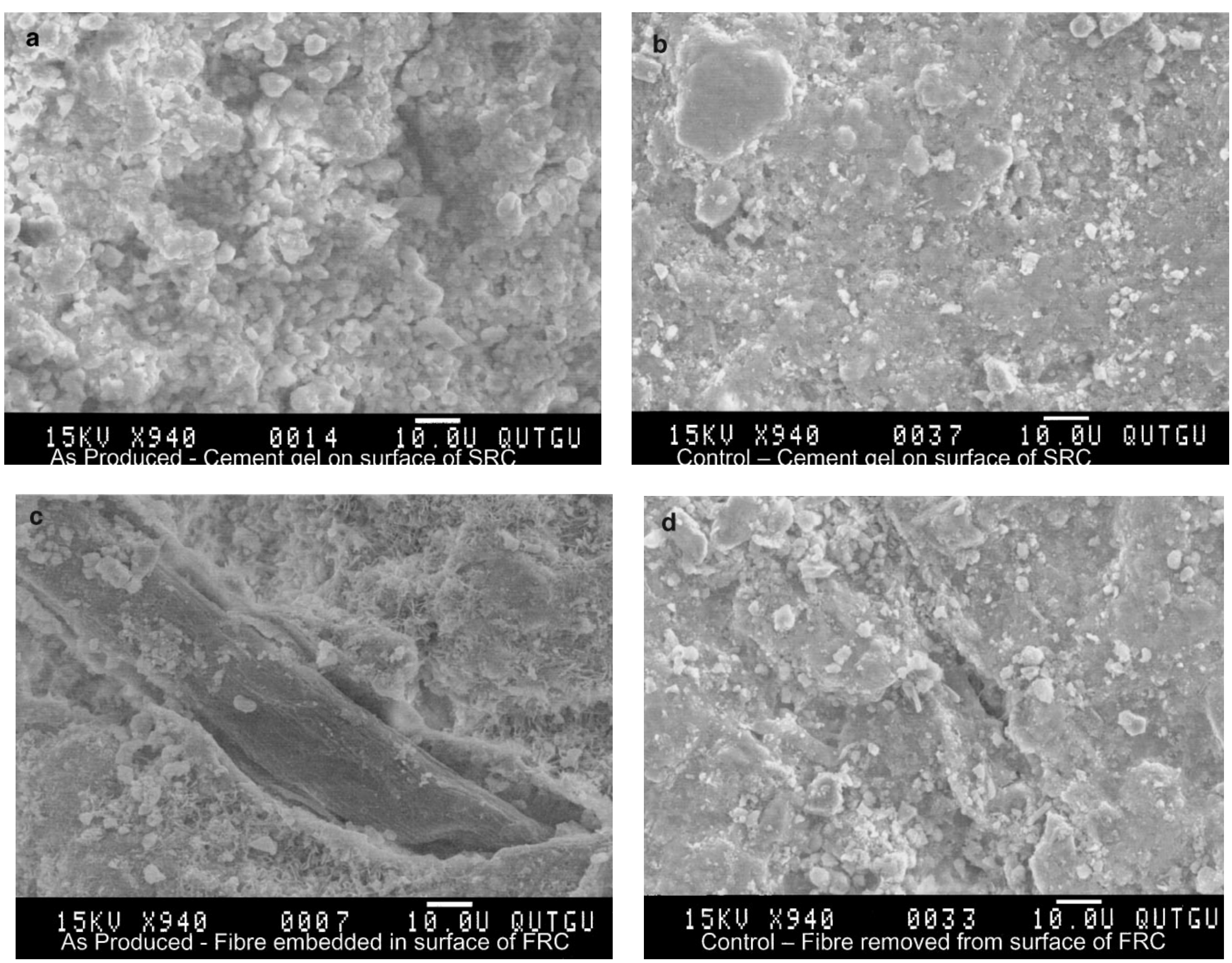

Fig. 5. Scanning electron micrographs of control samples of SRC and FRC.

6. Discussion of results

6.1. Baseline/control data — sample performance in water

As previously stated, both moisture content and age significantly affect the material characteristics of FRC. Subsequently, the sample set exposed to water for the duration of testing was included to provide an indication of the performance of both FRC and SRC in a nonaggressive situation as a means of gauging the effects of the test environments in isolation from these factors.

The effects of moisture and age have been accounted for in both Figs. 1 and 2, where the plot displays the difference between the baseline data and the measured performance in the test environments. In Figs. 3 and 4, it may be observed that both the strength and maximum tensile capacity of the pipe material do not change significantly over the exposure duration. It is difficult to identify any significant relationship between the control environment exposure duration and the strength characteristics of FRC from the test data.

Fig. 5 presents micrographs of both the SRC and FRC materials prior to testing and at approximately 520 days exposure in the control environment. High resolution SEM provides useful information on the morphology of the products of hydration and any products resulting from their degradation. An understanding of the micrographs in Fig. 5 provides the basis of analysis aimed at determining the mechanisms of degradation for each of the test environments.

As can be seen in Fig. 5(a) and (b), the nature of the cement matrix within SRC changed very little over the exposure duration within the control environment. While it is evident that the abrasive action of scrubbing has had some effect on the surface characteristics of the sample, it appears that these are superficial and relate only to the physical nature of the surface. The integrity of the cementitious material remains unaffected.

Consideration of the FRC material displayed in Fig. 5(c) gives rise to the question of the highly crystalline phase evident in the concrete matrix of the ‘as produced’ material. The rosettes of hexagonal plate like crystals have been determined through EDX to be uncarbonated tobermorite, produced from the reaction between C-S-H and silica under the autoclave curing conditions. Carbonation of this crystalline material results in its transformation to the cementitious material typical of the sample surface in Fig. 5(d). Fig. 5(c) and (d) also indicate the susceptibility of the cellulose fibres to the abrasive action of scrubbing as can be seen in Fig. 5(d) where there is an absence of surface fibres.

6.2. Gibson Island Sewage Treatment Facility

Figs. 1 and 2 indicate that FRC specimens exposed to the aerobic bio-mass of the Gibson Island Waste Water Treatment Plant have experienced the greatest variation to both the mid span wall thickness and surface dry saturated mass of the samples. Over an approximately 700-day exposure period, these coupons have displayed an average reduction in wall thickness in the order of 7% and a corresponding loss of mass in the order of 8.5%. To a lesser extent, the SRC coupons exposed to this environment also displayed reductions in wall thickness and sample mass in the order of 2.5%. Consequently, it appears that the observed changes in the FRC coupons may be attributed primarily to surface fibre degradation exacerbated by the scrubbing process, although the changes observed in the SRC samples indicate that this effluent may also prove detrimental to the performance of the concrete matrix. The properties of the effluent, highlighting the potentially aggressive nature of this exposure environment to concrete, are given in Table 1.

These results indicate that any deterioration present within the concrete matrix of FRC or SRC may be assumed to be a result of the level of ammonium within the sewage effluent. The expected effect of such deterioration is the leaching of lime from within the concrete matrix, progressively weakening it, without any outward signs of attack [6]. If in the form of ammonium sulphate, as expected in this situation, an increased threat to the integrity of the concrete matrix is through the production of expansive products resulting from attack by the sulphate ions. The use of SEM provides verification of this process.

Fig. 6 shows the surface of both SRC and FRC after approximately 700 days exposure to the effluent of Gibson Island Sewage Treatment Facility. Cracks are evident across the surface of both materials; it is interesting to note however, the difference in the size of these cracks. Typically, the cracks in the surface of the SRC are of the order of 5 μm while those in the surface of the FRC are only 1 μm. It is assumed that this may be attributed to the distribution of reinforcing fibres close to the surface of the FRC composite. Both materials show evidence of crystal formations within the cracks; closer observation based on morphology identified the crystal structure to be that of gypsum. Equipment limitations prevented confirmation of the composition of the crystal formation, as it typically

Table 1
Chemical analysis of Gibson Island effluent sample

Analysis description	Test result	Predicted effect on concrete [13]	
pH value	6.87	pH > 6.5	not considered particularly aggressive
Lime dissolving carbonic acid as free carbon dioxide (CO^2)	12 mg/l	$[CO^2] < 15$ mg/l	not considered particularly aggressive
Magnesium (Mg^{2+})	23 mg/l	$[Mg^{2+}] < 100$ mg/l	not considered particularly aggressive
Sulfate (SO_4^{2-})	71 mg/l	$[SO_4^{2-}] < 200$ mg/l	not considered particularly aggressive
Ammonium (NH_4^+)	28.6 mg/l	$15 < [NH_4^+] < 30$	slightly aggressive

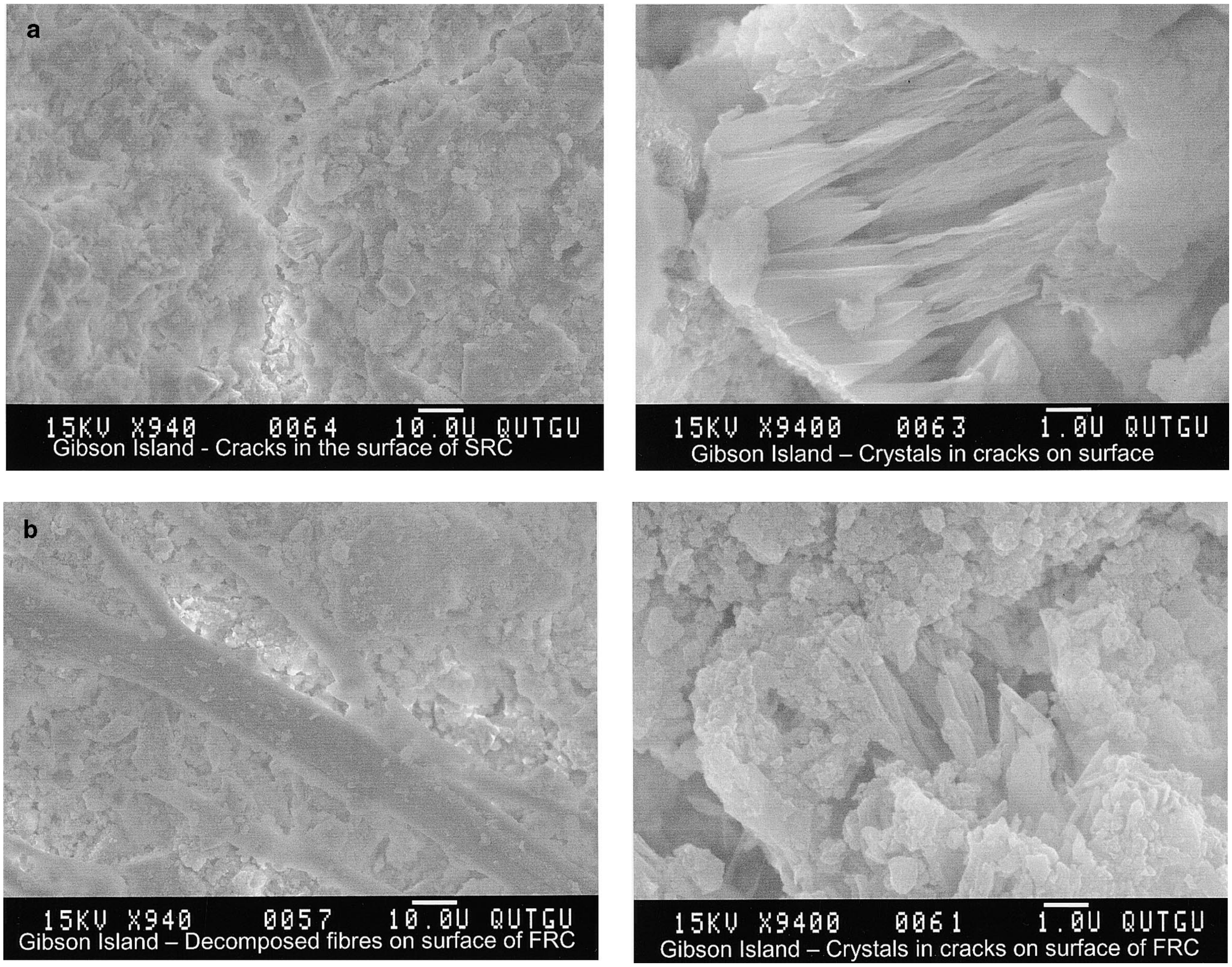

Fig. 6. Scanning electron micrographs of SRC and FRC exposed to the effluent of Gibson Island Waste Water Treatment Facility.

formed within the surface cracks, and subsequently fell into a shadow zone for energy dispersion X-ray analysis. Regardless, it appears that expansive formation of a crystalline substance, as a result of sulphate attack, has caused the cracking evident on the surface of both materials. The leaching of lime by the ammonium ions further enhances the deterioration process.

SEM analysis also provided confirmation of the nature of fibre degradation. Cellulolytic decomposition of the fibres is known to be very similar to acid attack, in that the decomposition is initiated in the amorphous regions of the fibre, breaking the fibres down into microfibrils. In this regard, the fibre retains, to a certain degree, its fibrous nature as is evident in Fig. 6. It is interesting to note the quantity of fibres on the surface of the material is similar to the quantity at production. This indicates that the rate of degradation of the concrete matrix is greater than the rate of degradation of the fibres. This becomes evident when compared with the FRC samples exposed to the anaerobic conditions of Suncoast Sewage Treatment Facility.

Despite the degradation of the fibres and the concrete matrix, Figs. 3 and 4 indicate that the FRC pipe sections do not display a significant loss in pipe strength, nor in the maximum tensile capacity of the reinforcing fibres. These results indicate that the observed degradation processes are surface reactions only and that although the pipe section is susceptible to degradation in an aerobic sewage environment, the effect of such an environment on long-term pipe performance is of little consequence.

6.3. Suncoast Sewage Treatment Facility

The samples exposed to the anaerobic conditions of the Suncoast Treatment Facility performed in a similar fashion to those exposed to the aerobic environment of Gibson Island. Again both the FRC and SRC samples display a reduction in mid span wall thickness and surface dry saturated mass. The observed changes in the SRC of 1% and 1.5%, respectively, again indicate that this exposure environment may be detrimental to the performance of the

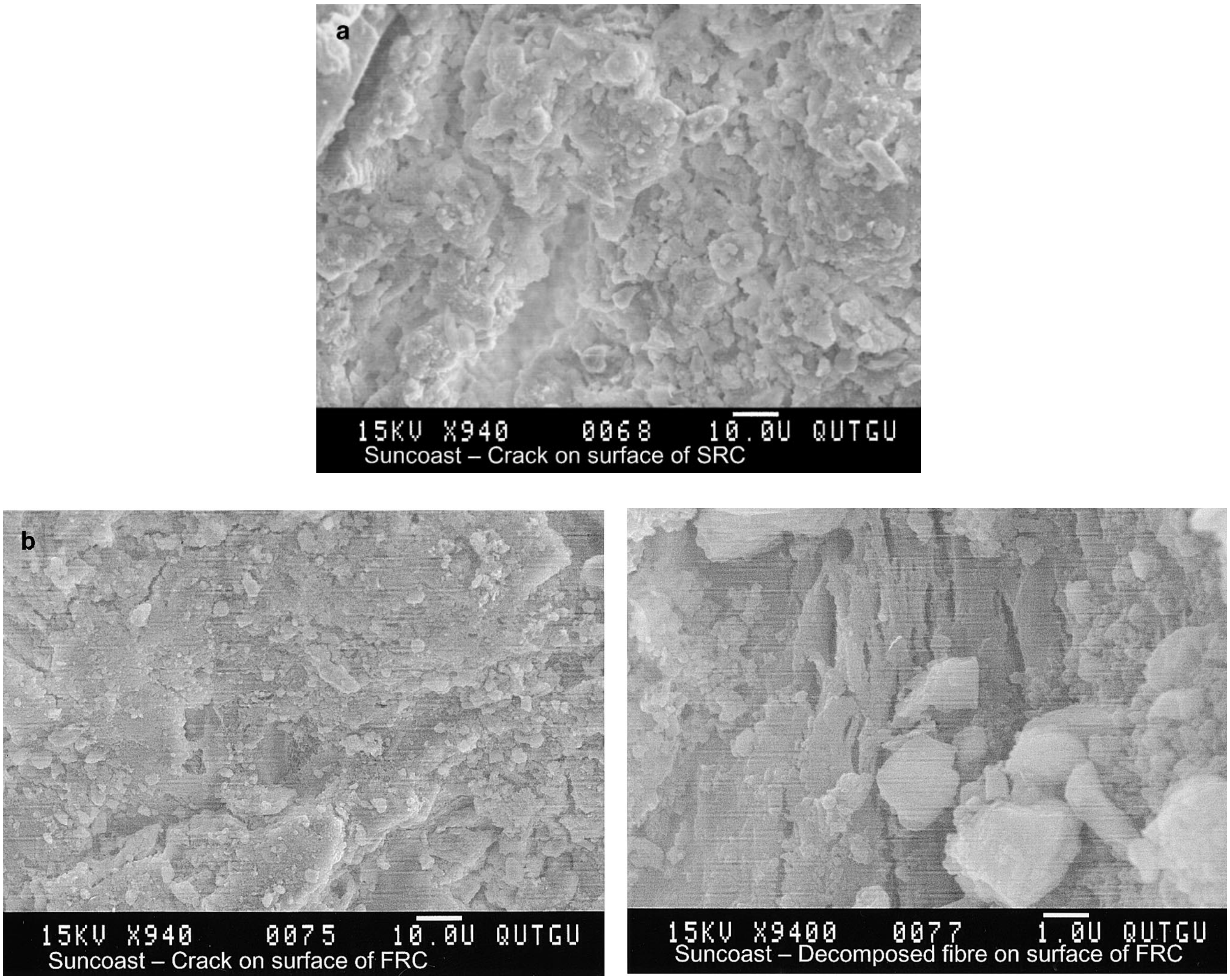

Fig. 7. Scanning electron micrographs of SRC and FRC exposed to the effluent of Suncoast Waste Water Treatment Facility.

concrete matrix. The results of chemical analysis of the effluent (Table 2) confirm this may be attributed to the ammonium content of the effluent. The changes in the FRC properties (loss in wall thickness in the order of 5% and a loss of mass in the order of 3.5%) indicate that, although not as aggressive as the Gibson Island test environment, this anaerobic environment also has the potential to decompose the cellulose fibres.

Table 2
Chemical analysis of Gibson Island effluent sample

Analysis description	Test result	Predicted effect on concrete [13]	
pH value	6.96	pH >6.5	not considered particularly aggressive
Lime dissolving carbonic acid as free carbon dioxide (CO^2)	2 mg/l	$[CO^2] < 15$ mg/l	not considered particularly aggressive
Magnesium (Mg^{2+})	29 mg/l	$[Mg^{2+}] < 100$ mg/l	not considered particularly aggressive
Sulfate (SO_4^{2-})	104 mg/l	$[SO_4^{2-}] < 200$ mg/l	not considered particularly aggressive
Ammonium (NH_4^+)	21.3 mg/l	$15 < [NH_4^+] < 30$	slightly aggressive

Again, closer analysis of the samples using SEM was undertaken in order to confirm the degradation processes. Fig. 7 shows the surface of the SRC and FRC materials after 700 days exposure to the anaerobic environment of the Suncoast Sewage Treatment Facility. Unlike the samples from Gibson Island, both the FRC and SRC from the Suncoast Sewage Treatment Facility are very similar in appearance, with the principal difference being the size of the surface cracks. While the SRC displays cracks in the order of 10 μm, the cracks in the surface of the FRC are only about half this size. Fibre distribution, and subsequent reinforcement, is considered to be the reason for this difference. It is interesting to note that there is no evidence of crystal formation within the cracks of either sample material. As with the effluent of Gibson Island, it would be assumed that the combined action of the leaching of lime by ammonium and the formation of gypsum from the sulphates would result in the cracking that is evident on the surface. The lack of crystal formation within the cracks indicates that the leaching action of the ammonium ion is the dominant degradation mechanism.

In addition to the degradation of the matrix, the FRC material exhibits degradation of reinforcing fibres. The lack of fibres visible on the surface of the material sample indicates that within the anaerobic conditions of Suncoast Sewage Treatment Facility, the rate at which the fibres decompose is greater than the rate of degradation of the concrete matrix. Observation of the fibres reveals a similar decomposition process to that observed in the FRC sample exposed to the aerobic conditions of Gibson Island Sewage Treatment Facility.

As with the pipe samples exposed to the Gibson Island effluent, Figs. 3 and 4 do not indicate any significant trends in the strength characteristics of the FRC pipe samples throughout the exposure duration. Given that there is no appreciable loss in strength or maximum tensile capacity for the pipes, it may be concluded that the reactions are surface reactions only. This is also manifested by the similar reduction trend in both sample wall thickness and sample mass shown in Figs. 1 and 2, indicating that the mass loss is primarily due to wall thickness reduction, not matrix degradation.

6.4. Sulphuric acid testing at QUT

The final exposure environment considered was sulphuric acid with a pH ranging between 4.8 and 5.5. This environment is known to be the principal cause of failure in concrete sewers, and is classified as a highly aggressive environment with regards to the deterioration of concrete [13]. Over the 700-day exposure period, both the FRC and SRC samples have displayed a loss in mid span wall thickness and surface dry saturated mass. The SRC displayed losses of 0.5% wall thickness and 1.5% mass, while the FRC displayed losses of 2% wall thickness and 3.5% mass. The observed differences in these results indicate a greater susceptibility of FRC to acid attack than SRC and one assumes that this difference must be attributed to fibre

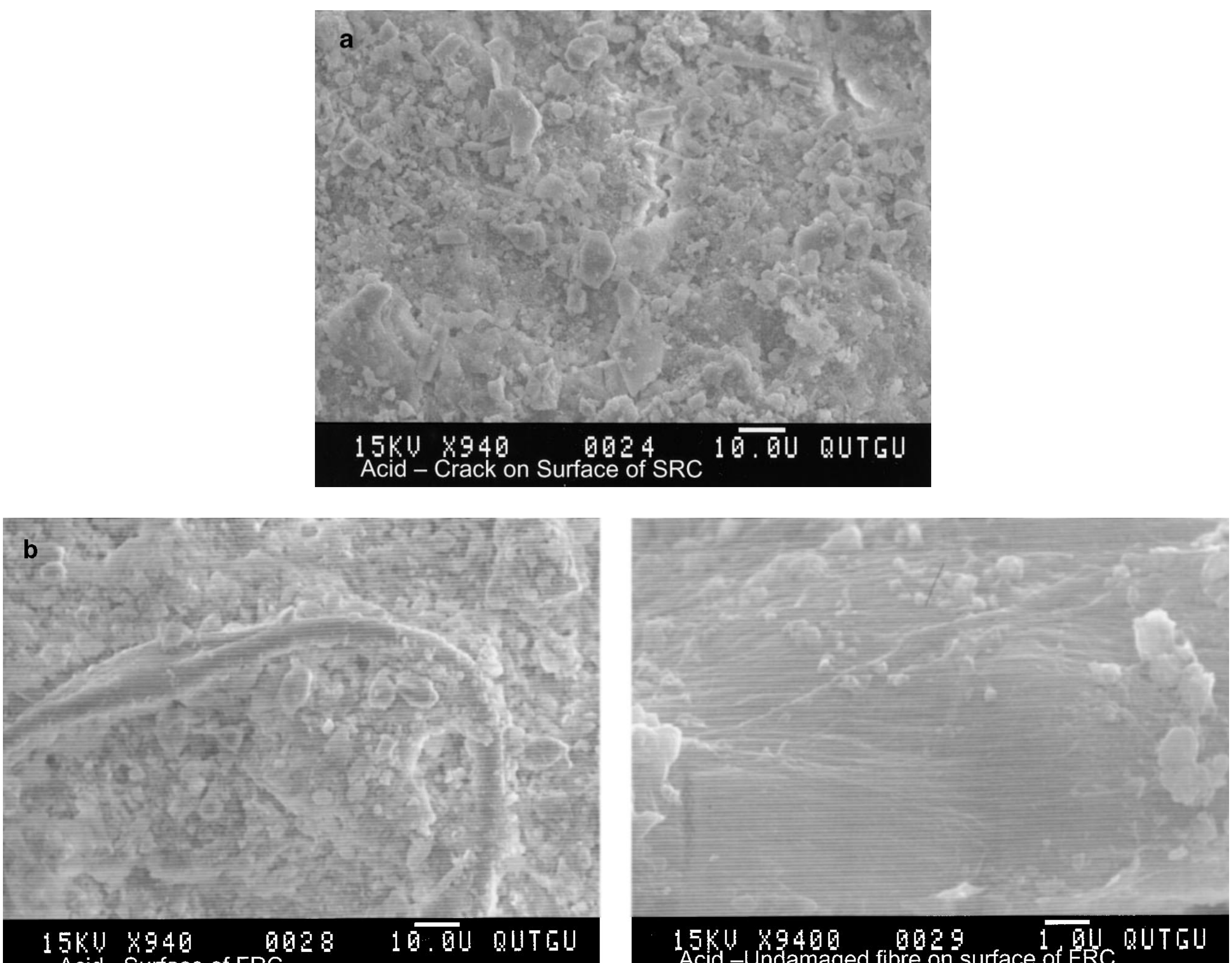

Fig. 8. Scanning electron micrographs of SRC and FRC exposed to sulphuric acid.

degradation. By way of confirmation, SEM was utilised; the micrographs for which are displayed in Fig. 8.

As with the other test environments, the surface of both the SRC and FRC coupons show significant cracking; the cracks in the SRC in the order of 10 μm while the FRC are about half this size. There are no crystals evident within any of the cracks, and the FRC does not have many fibres evident on the surface. The samples from this acidic environment are very similar to those retrieved from the Suncoast Waste Water Treatment Facility. This is not surprising given that the dominant mechanisms for degradation of the concrete matrix in both environments is the leaching of the lime by the test environment. Again Figs. 3 and 4 show, like the samples retrieved from the Suncoast Waste Water Treatment Facility and the Gibson Island Sewage Treatment Facility, that there are no significant trends in the strength characteristics of the FRC pipe samples.

Observation of the fibres, however, shows no change to the integrity of the fibre, despite the distinct lack of visible surface fibres. This indicates that the fibres are not susceptible to acidic degradation at this pH, although the scrubbing action in this test environments has effectively removed the surface fibres. This is similar to the fibre removal evident within the control environment. Consequently, the observed changes in wall thickness, mass and strength characteristics of the FRC may be attributed to the characteristics of the concrete matrix, and the integrity of the fibre–matrix bond. This is surprising given that autoclaved concretes are generally more durable in acidic environments than air-cured concretes due to their reduced lime content.

7. Conclusions

In the utilisation of concrete pipes for the transportation of sewage, durability is a key aspect to their satisfactory long-term performance. Consequently, the long-term performance of FRC pipes in sewage applications is vital if these pipes are to be employed in infrastructure developments.

This research program gauged the durability characteristics of FRC pipes against the historically proven performance of SRC pipes in sewage applications. Within such applications, it is principally the production of sulphuric acid by biological processes that results in pipe failure. An additional concern in utilising FRC pipes within sewage systems is the potential for biological degradation of the cellulose fibres.

Through exposure to aggressive acidic and biological environments aimed at monitoring the performance of FRC when compared with SRC, it has been found that while the mechanisms for degradation of the concrete matrix have been similar, the performance of the FRC material is less favourable in all environments tested. When utilised in the form of pipes however, consideration must be given to the nature of reinforcing within both materials. While the FRC composite displays a greater loss in wall thickness and mass than SRC for the exposure duration, the continuity of the fibre reinforcement throughout the composite means that the integrity of the pipe is not threatened while the pipe strength meets the design loads. In comparison, the performance of SRC pipes could be expected to deteriorate rapidly once concrete protecting the steel cage reinforcement is damaged.

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