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SEM ANALYSIS OF CFRP STRAND FOR USE IN HIGH CAPACITY PERMANENT GROUND ANCHORS

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Abstract

Steel strand ground anchor system using stress relieved post tensioned strands are vulnerable to corrosive attack from aggressive ground environments. Current permanent ground anchor standards require the use of double protection systems encapsulating the steel strands, to ensure a serviceable design life. In recent years, where steel reinforcement use was restricted due to aggressive ground conditions, FRP reinforcement was successfully used as a durable construction alternative. Whilst carbon fibre (CFRP) strands have been researched and developed for use in prestressed concrete members such as bridge construction, minimal research has been devoted to developing FRP strands for use in high capacity ground anchors.

This paper summarises current research knowledge and best practices for use of CFRP strands in ground anchor systems. Research work reported in this paper involves investigation of CFRP strand performance, when exposed to extreme aggressive environments. A series of six month long experiments are currently in progress studying these durability effects over a range of accelerated conditions including temperature and concentration levels, whilst specimens are in an unstressed state. This paper presents results of SEM analysis on unstressed CFRP specimens subjected to an alkaline and acidic based groundwater solution and a neutral solution tested under accelerated conditions (60^{O}C and 30^{O}C with increased salt concentration) over a six month period.

INTRODUCTION AND BACKGROUND

High capacity ground anchors currently employ the well established steel strand system using stress relieved post tensioned strands [1]. Although such systems provide rugged tendons with readily available hardware, they are vulnerable to corrosive attack from aggressive environments. Current permanent ground anchor standards require the use of double corrosion protection systems encapsulating the steel strands, to ensure a serviceable design life.

FRP's are characterised by their superior resistance to aggressive environments, compared to steel. Where steel reinforcement has been restricted due to aggressive ground conditions, minimal alternatives have been available for industry use until FRP reinforcement was developed and successfully used as a durable construction alternative. Extensive research has been conducted on FRP as a substitute for conventional steel reinforcement; however there is minimal knowledge on FRP limitations, especially its behaviour over prolonged exposure to aggressive ground environments whilst in a stressed state.

LIMITATIONS OF STEEL STRAND GROUND ANCHORS

Corrosion in steel tendon ground anchors occurs as a consequence of in-homogeneities or impurities in the steel tendon or grout, or by the existence of salts, sulphates and other dissolved solids present in grout mixtures, soils or groundwater [2].

To eliminate risk of corrosion, international standards [3] established a double corrosion protection system as a minimum level of protection required for permanent ground anchors (Figure 1). Double corrosion protection must be applied over the tendon bond length, tendon free length, the anchor head and the transition between the anchor head and the tendon free length [4, 5].

Littlejohn [6] reported on 35 known cases of corrosion related failures to steel tendon ground anchors, concluding that free length corrosion comprised 60% of failures, 34% of failures occurred at the anchorage head and only 6% of failures occurred in the fixed anchor length. Catastrophic structural failures can occur as a direct result of ground anchor failure due to corrosion (Figure 2).

Littlejohn emphasised that the small percentage of failures within the fixed anchor length was a result of inadequate grout placement. Further recent case studies are presented by Littlejohn and Mothersille [7, 8].

Steel tendon corrosion occurs locally where the tendon intersects a crack in the surrounding grout, or as a result of damage to the corrosion protective sheaths [9]. Grout cracks occur as a result of either shrinkage strains during curing or tensile loading of the anchor. Due to grout micro cracking, majority of standards do not permit grout to be considered as one of the two means for corrosion protection. Weerasinghe and Anson [10] and Mothersille [11] provided project examples where corrosion occurred above and below the anchor head, resulting in anchor strength reduction (Figure 2).

Tendon material choice currently limits ground anchor development. The need to protect the ground anchor system from corrosion performs an integral element of a permanent ground anchor.

Figure 1: Longitudinal section - double corrosion protection through ground anchor bond length [7, 11].


(a) (b)

Figure 2: Failure of anchored quay wall (b) corroded barrels and wedges in anchor head (c) lack of corrosion protection behind anchor block [7, 11]

FIBRE REINFORCED POLYMER (FRP) MATERIALS

Fibre reinforced polymer materials contain aligned continuous organic (aramid or carbon fibre) or inorganic (glass fibre) filaments embedded in a polymer matrix and shaped into a product for use. Organic filaments are the primary choice for ground anchors [12]. North America is continuously developing and refining the use of inorganic filaments as a substitute for steel in concrete reinforced structures [13, 14].

For all FRP materials, a polymetric matrix is used to bond the fibres, protect the fibres against environmental effects and assist in the equalization of fibre forces and load transfers in the transverse direction. Thermoplastic and thermoset polymers can be applied with FRP fibre filaments to form an FRP composite material. Thermoset polymers including epoxy, polyester and vinyl ester are preferred resins for FRP material selections in permanent ground anchor applications [4, 15].

DURABILITY OF CFRP IN AGGRESSIVE GROUND ENVIRONMENTS

Ground anchors are commonly exposed to both acidic and alkaline ground conditions depending on ground mineral content, soil/rock type, age and groundwater flow path. It is essential to understand the limitations to ground anchorage materials especially when exposed to aggressive ground conditions whilst in a stressed state. Conventional ground anchors use multiple layers of HDPE sheaths or combined HDPE and steel sheaths to protect steel strand from external environments.

This paper reports on an experimental analysis investigating the durability of various CFRP strand materials exposed to two different aggressive groundwater conditions and a neutral condition at elevated temperatures under unstressed conditions. This investigation aimed to establish if corrosion protection is required for high capacity ground anchorages systems; and if so, what levels of corrosion protection are needed to ensure a serviceable design life.

Factors affecting CFRP durability

Steel is deemed isotropic and homogenous in comparison to anisotropic and heterogeneous CFRP reinforcement [5, 8]. Behaviour of the bond between the steel and the cementitious product in conventional steel reinforced concrete is generally influenced by the concrete strength [16]. On the other hand, FRP bond behaviour in FRP reinforced concrete products is influenced by numerous factors as indicated by Nanni et al. [16] including; fibre type, matrix type, FRP geometry, and FRP manufacturing process.

Micelli and Nanni [17] performed experiments to investigate the durability of FRP reinforcement bars on concrete structures, indicating various damage mechanisms for FRP reinforcement which must be considered relevant to ground anchors including; fluid absorption and influence on physical/mechanical properties, creep and stress relaxation, fatigue and environmental fatigue damage and weathering. These mechanisms considered as a result of attack by external agents relevant to the ground anchor including moisture and aggressive solutions (within groundwater), alkaline environment (within both the grout and groundwater), and fatigue loads (from superstructure).

Micelli and Nanni [17] further suggests that the rate of degradation of polymer composites exposed to a fluid environment is related to the rate of sorption of the fluid, concluding that the absorption behaviour of a polymer composite depends on the type of fluid the composite it is exposed to, concentration levels of fluid that composite polymer is exposed to, temperature, damage status of composite polymer, applied stresses to composite polymer, and chemical structure of matrix and the fibre/matrix interface within the composite polymer. As a result of the polymer composition, polymers are classified as a viscoelastic material and can exhibit creep and stress relaxation to greater extents than steel reinforcements.

Aggressive groundwater environments

Aggressive ground conditions generally relate to the aggressive nature of either the ground (soil/rock/contaminated or hazardous waste fill) or the groundwater by means of increased levels of minerals, ions or contaminants. Groundwater can be defined as the subsurface water located in soil pore spaces and in the fractures of geological formations [4]. Due to the location of groundwater, the presence of contaminants due to soil/rock condition, mineralogy of the surrounding ground, environmental factors caused by human alterations to the environment (mining, industrial leakage, etc) has a part in providing a certain quality to the groundwater [18]. Aggressive groundwater is commonly understood as water which is either acidic or alkaline. The various ion levels and the total dissolved solids (TDS) determine the aggressive nature of groundwater.

Aggressive groundwater in Australia is commonly measured by the concentration levels of Sulphate (SO_4^{2-}), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+) and Chloride (Cl^-) [19]. AS3600 [20] exposure classification recommends that any soil with a pH<4.0 or with groundwater>1000mg/L of Sulphate shall be deemed aggressive. Walton [19] concluded that any groundwater environment can be deemed aggressive should the TDS exceed 1000mg/L where the TDS comprises of one or more of the above mentioned minerals.

Acidic aggressive groundwater is commonly located in soils with groundwater close to the surface or near costal regions in Australia where Sulphate levels are excessive [21]. Sodium Hydrogen Sulphate ($NaHSO_4$) is a common solution found in highly acidic groundwater where Sulphate is present. It is the ion combination which can be present in Australia's aggressive groundwater that can have altering effects on steel properties compared with the effects of concrete pore water.

Common groundwater in Australia has a pH range between 5.0 and 8.0. Extreme alkaline groundwater is considered to have a pH range between 8.0 and 10.0. These extreme alkaline groundwater conditions are associated with the inclusion of Sodium Bicarbonate ($NaHCO_3$) [19]. Groundwater with high concentrations of Hydrogen Carbonate (HCO_3^-) is commonly associated with moderate alkaline groundwater. Acidic groundwater is classified as having a pH<5.0. Extreme acidic groundwater (pH less than 2.5) contains free acids. Groundwater with varying amounts of mineral acids from sulfide sources or within organic acids is considered to be moderately acidic [19].

CFRP absorption of aggressive groundwater solutions

A critical aspect of FRP durability is its absorption behaviour. Diffusivity and gravimetric measurements can be used to monitor this behaviour. Moisture can permeate into different FRP products to different extents, depending upon the number of molecular and microstructural aspects, polarity of the molecular structure, degree of cross-linking, degree of crystallinity, presence of residual monomers and the FRP's surface properties [17]. Micelli and Nanni [17] and ACI440.3R-04 [22] method for analysing CFRP's rate of absorption provide methods to numerically calculates material absorption. Detailed research into unstressed and stressed CFRP strand ground anchors have been presented by Sentry et al. [5].

CFRP DURABILITY INVESTIGATION IN AGGRESSIVE GROUND ENVIRONMENTS

Investigation into the durability effects of CFRP strands in aggressive ground environments is being undertaken at Monash University. This research investigates on a micro level what effects various extreme aggressive ground environments have on various CFRP materials. The research aims to provide a greater understanding of how CFRP strand works under stressed and unstressed conditions in extreme ground environments when commercially used in high capacity permanent ground anchors.

Experimental procedure

Specimens were cured in three differing solutions in an unstressed state for a period of up to six months. The specimens were exposed to the solutions at elevated temperatures 60^{O}C. Upon removing the specimens from the solutions, macro and micro analysis was carried out, investigating if there were any changes to the materials physical properties as a result of the curing.

Scanning electron microscopy (SEM) was used for the micro analysis. SEM analysis is an excellent method to analyse micro-structural change to the matrix, FRP fibres and the external protective barrier present on CFRP specimens. Assessment on the degeneration of the external protective barrier and internal fibre/epoxy bond can assist in understanding absorption rates and what effects this may have on the specimens overall tensile performance. Composition analysis was conducted on selective specimens where SEM analysis indicated exposed carbon fibre regions where the potential deterioration of the CFRP could be present due to aggressive solution attack. Composition analysis determines what chemicals are present at selected locations on the specimen.

Material Properties

Two CFRP strands were adopted for this investigation (Figure 3). Material properties are as per Table 1.

Table 1: Technical properties for CFRP test specimens being used in research project [23, 24]

Property	Units	CFCC (Tokyo Rope)	HS25x2 (Sireg)
Dimensions			
Width	mm	-	25
Diameter	mm	15.2	-
Nominal Thickness	mm^2	-	2
Effective Cross Sectional Area	g/m	113.6	32
Linear Weight		226	97
Carbon Fibre			
Minimum fibre volume ratio		0.62	0.64
Density	g/mm^3	1.5	1.8
Tensile strength	MPa	4200	4900
Elastic modulus	GPa	240	78
Resin			
Type		modified epoxy	Vinylester
Density	g/mm^3	1.6 - 2.0	1.15
Tensile strength	MPa	80	>55
Product			
Tensile strength	MPa	2200	2500
Elastic modulus	GPa	141	140

Figure 3: Materials being used in investigation

Aggressive Groundwater solutions

Two aggressive solutions and one neutral solution were used to replicate groundwater conditions in this investigation. All aggressive solutions had a total dissolved solid (TDS) concentration much great than 1,000mg/L, as recommended by AS5100[25] and AS3600 [20]. The following solutions were used:

Acidic groundwater	→	$NaHSO_4 + NaCl^*$
Alkaline groundwater	→	$NaHCO_3 + NaOH + NaCl^*$
Neutral groundwater	→	H_2O

Note: * = added to increase salinity of solution to further accelerate aging of specimens

A pH of 9.5 (±0.5) was maintained for the alkaline aggressive groundwater solution; a pH of 1.0 (±0.5) was maintained for the acidic groundwater solution; while the neutral solution had a pH of 7.0 (±0.5).

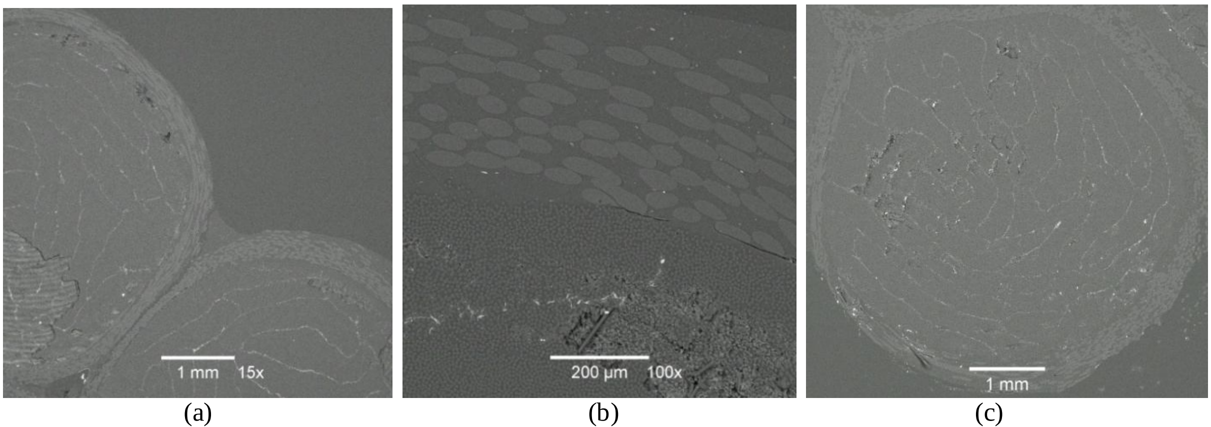
Results and Discussion

Scanning electron microscopy (SEM) was used to investigate what micro-structural damage had occurred to the CFRP material on a micro level as a direct result of exposure to the aggressive solutions. Absorption analysis and ultimate tensile assessment were also conducted, in this research, to assess tensile performance of the CFRP specimens post exposure to the aggressive solution. The combination of these assessments aims at providing a greater understanding to how the materials perform under extreme aggressive conditions. The combined results are not published within this paper.

No signs of fibre deterioration were observed during six months of sample curing at $60^{O}C$ in a neutral solution. Figure 4 indicates that the outer layer of the CFCC strand has remained intact during its curing process. These SEM results are in correlation with the macro visual inspection observed when removing specimens from the curing tank.

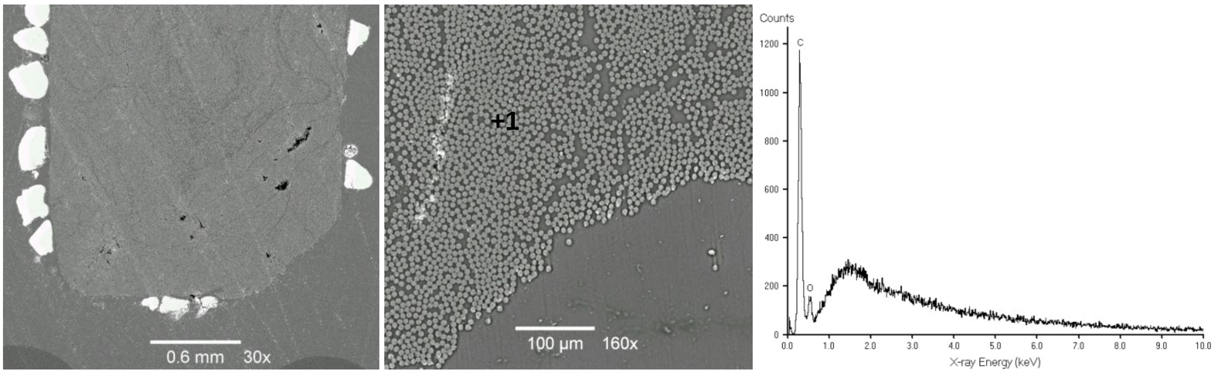
As with the CFCC material, no signs of fibre deterioration was observed during the six months of curing the HS25x2 samples at temperatures of $60^{O}C$ in the neutral solution (Figure 5).

SEM analysis of CFCC samples cured in acidic solution (Figure 6). Although the specimens showed no signs of deterioration (either outer layer or inner fibres) sections of the inner fibres were shown to be disorientated (Figure 6b) with pluming of some acidic solution attack on the outer edge of the fibre/epoxy interface (Figure 6c and d). Closer SEM analysis on these sections indicated microscopic localised sections of contaminated CFCC strand. Further research needs to establish if this minimal localised contamination will cause any long term property effects.



(a) (b) (c)

Figure 4: CFCC strand cured at $60^{O}C$ in neutral solution (a) 1 month specimen; (b) 3 month specimen; (c) 6 month specimen.

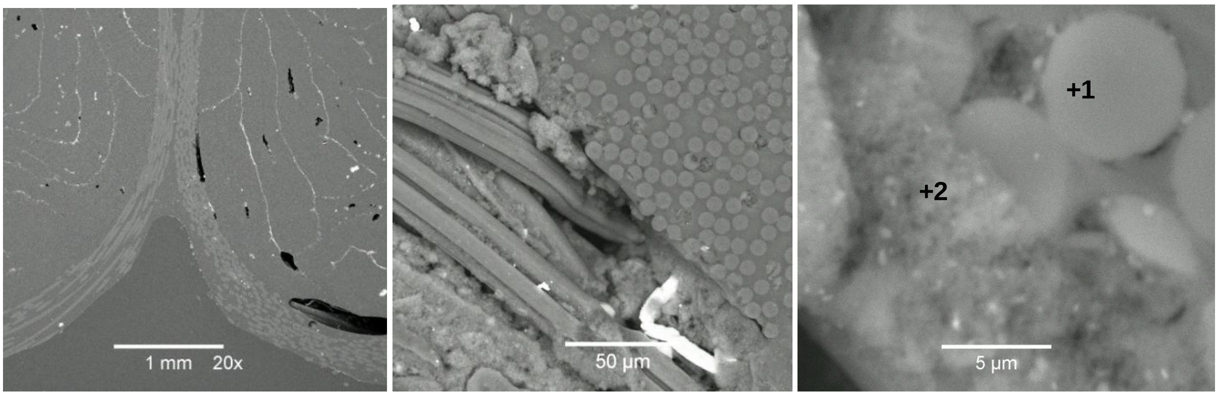


(a) (b) (c)

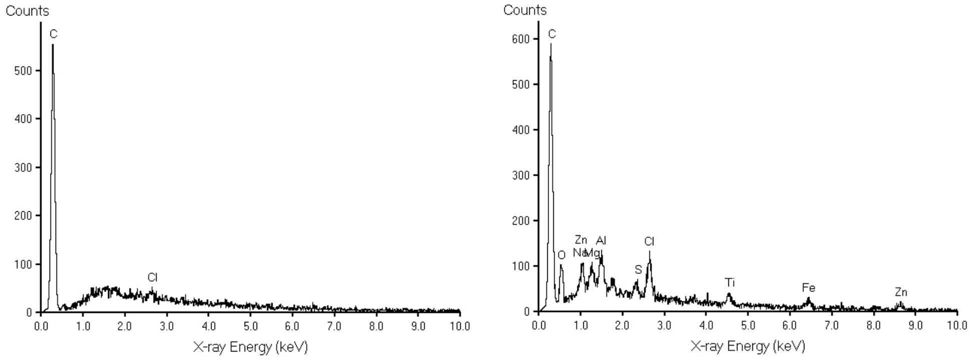
Figure 5: HS25x2 strand cured at 60^{O}C in neutral solution (a) 1 month specimen; (b) 3 month specimen; (c) chemical analysis of carbon fibre filament (point 1)

Analysis of the HS25x2 samples in the acidic solution (Figure 7) showed immediate signs (from 1 month curing) of contamination of the fibres and resin by the aggressive solution. This is quite understandable, as this product does not have a protective layer around the outer perimeter of the fibres allowing direct contact between fibres/resin and groundwater. Further investigation in the effects of the contamination adhering to the HS25x2 material must be carried out prior to further analysis.

SEM analysis on CFCC specimens exposed to alkaline aggressive groundwater solution did not show any global signs of deterioration over a six month exposure period at temperatures of 60^{O}C (Figure 8). Figure 8b shows a location of localised outer fibre layer damage. Three points were analysed including the different sections of the outer layer and the inner carbon fibres. The graphical results for the three points are also represented in Figure 8. Figure 8c shows composition analysis of the specimen at the point where damage to the outer layer was observed. The composition analysis identified chloride, silicone and magnesium present. These are minerals found within the aggressive alkaline ground solution. The iron and aluminum present may be a result of the cutting tools used in specimen preparation. Composition analysis of the outer layer away from the damaged section (Figure 8d) identified only carbon and oxygen; indicating the minerals observed in Figure 8b are that of the aggressive solution. Composition analysis of the carbon fibres located near the damaged section of the CFCC specimens (Figure 8e) identifies only carbon present. This concludes that there was no chemical attack on the carbon fibres due to the break in the outer layer.

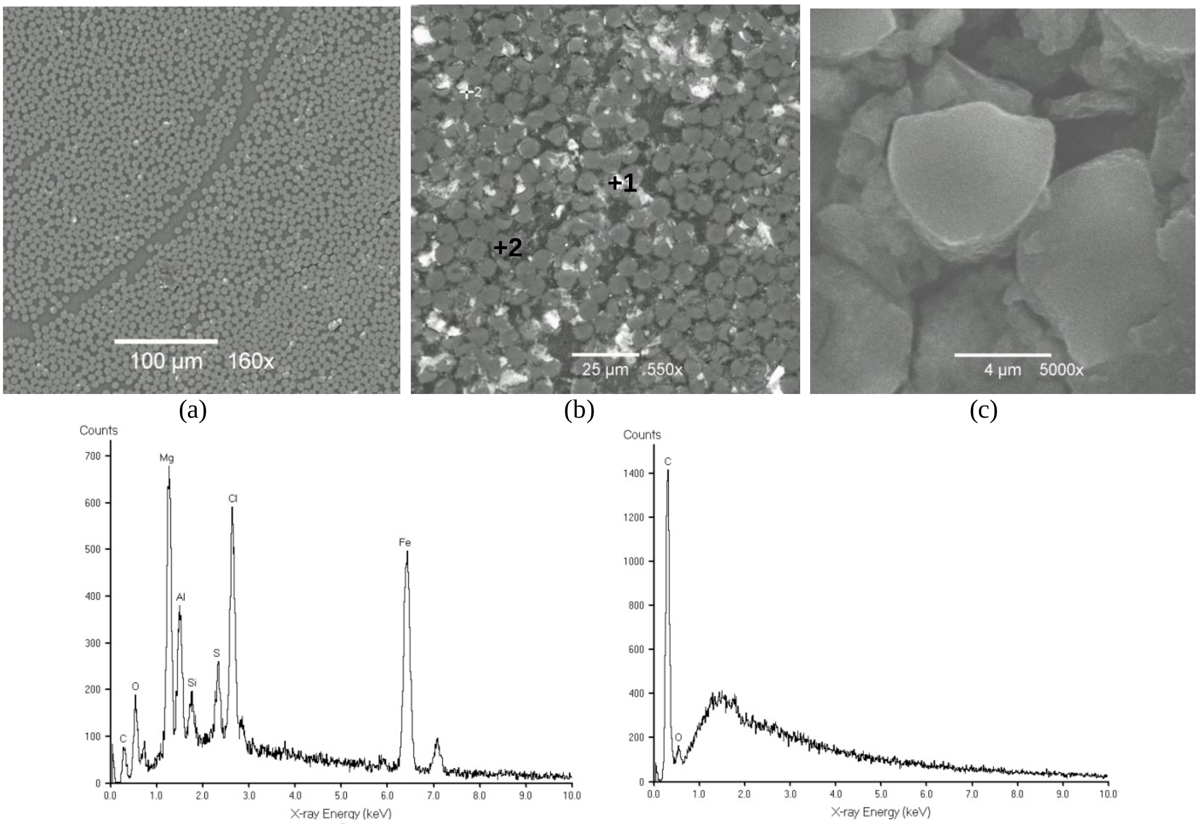


(a) (b) (c)



(d) (e)

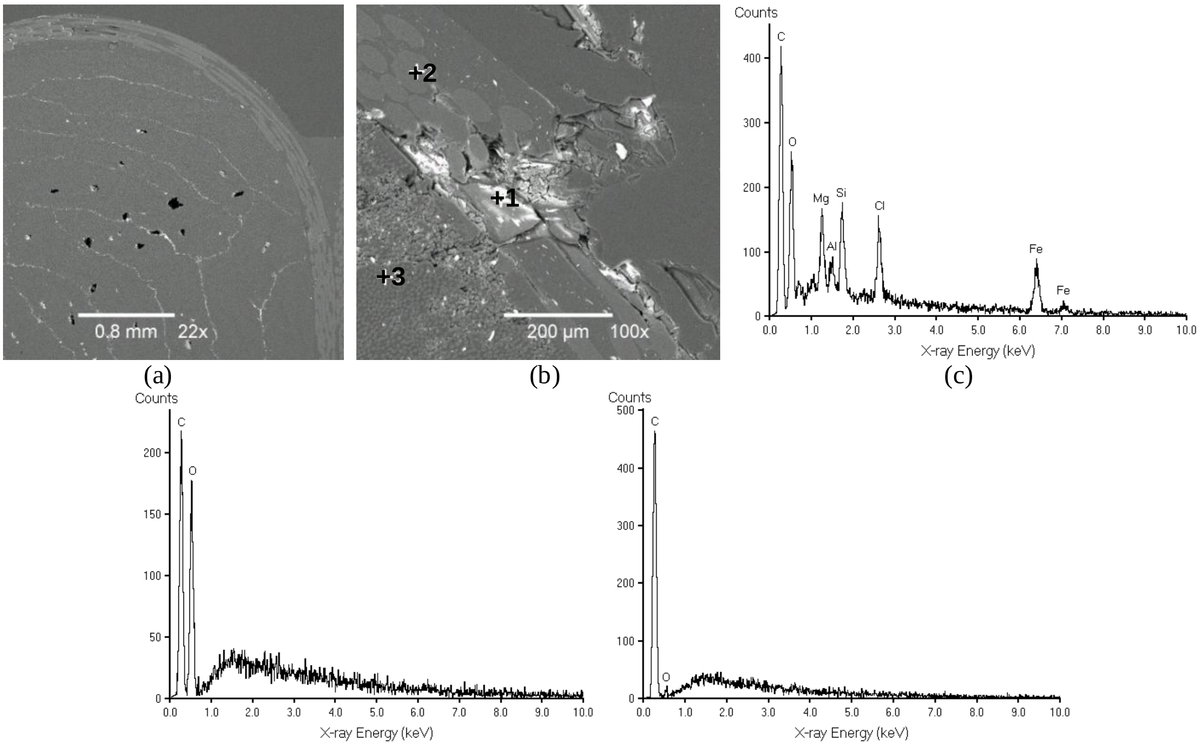
Figure 6: CFCC strand cured at 60^{O}C in acidic solution (a) 6 month specimen – wires intact; (b) localised fibre damage located just inside of intact outer layer; (c) zoomed section (4000x) of localised contaminated fibres; (d) chemical analysis of carbon fibre filament (point 1); (e) chemical analysis of contaminated carbon fibre (point 2).



(a) (b) (c)

(d) (e)

Figure 7: HS25x2 strand cured at 60^{O}C in acidic solution (a) 1 month specimen; (b) 1 month specimen with localised contamination of fibres by acidic solution; (c) zoomed section (5000x) of localised contaminated fibres; (d) chemical analysis of contaminated carbon fibre (point 1); (e) chemical analysis of carbon fibre (point 2).



(a) (b) (c)

(d) (e)

Figure 8: CFCC strand cured at 60^{O}C in alkaline solution (a) 3 month specimen – wire intact; (b) localised are where damage was observed in outer layer; (c) Chemical analysis showing elements imbedded in outer layer (point 1); (d) chemical analysis of intact outer layer fibre (point2); (e) chemical analysis of carbon fibre filament (point 3)

FUTURE RESEARCH WORKS

Results reported herein are part of a progressive report on the durability and absorption effects of CFRP materials with long term exposure to aggressive groundwater solutions under various conditions including, increased temperature and when specimens are exposed to these situations in a passive and a stressed state. This paper has reported the SEM analysis on specimens exposed to aggressive solutions in an unstressed state at an elevated temperature of 60^{O}C.

Research into long term effects of CFRP strands exposed to aggressive groundwater solutions at various elevated temperatures in unstressed and stressed conditions are currently being conducted at Monash University.

CONCLUSION

Although recent developments to conventional steel tendon ground anchors have improved corrosion protection, the implementation of FRP's into the construction industry provides a durable construction alternative. This paper presented results on a durability study, currently being conducted at Monash University, using SEM analysis to study the micro-structural effects various aggressive groundwater solutions have on different CFRP strands.

Indicative results at an elevated temperature of 60^{O}C in an unstressed state indicate that there is potential for aggressive solution to absorb into the fibres. Further investigation into the effects of this absorption including rates of absorption and the change in material strength parameters as a result of the chemical contamination is currently being completed at Monash University.

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