Durability performance of CFRP strand in Permanent Ground Anchors

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ABSTRACT

Although permanent ground anchor technology has advanced in leaps and bounds over the past two decades, the focus of anchor technology has been on developing techniques to minimise the risk of component and system failure due to corrosion. The advancements in structural materials available in the market in recent years have enabled research into alternative materials for permanent ground anchor systems. Carbon fibre has become a significant structural alternative throughout North America for bridge and building construction as well as repair and structural strengthening of deteriorated/corroded structures. These advancements and the necessity to investigate alternative materials for anchor systems have lead to research in understanding the long term performance effects of using carbon fibre products as an alternative to steel tendons in permanent ground anchors. Advanced research works at Monash University and Geotechnical Engineering investigated the durability performance of various available CFRP strands when used as an alternative to conventional steel tendons in permanent ground anchor systems. Research works included durability performance effects of CFRP strand when exposed to extreme aggressive ground environments under unstressed and stressed conditions at elevated temperatures over a six month curing period; bonding effects of CFRP strand in a cementitious grout; anchorage effects of CFRP strand in ground anchor systems; and full scale gun barrel assessment. The paper summaries the findings from the durability assessment of CFRP strand in aggressive ground environments and how these findings can assist in developing a CFRP permanent ground anchor system.

Keywords: Carbon fibre reinforced polymer, ground anchor, durability, fibre reinforced polymer, tendon.

1 INTRODUCTION

High capacity ground anchors currently employ the well established steel strand system using stress relieved post tensioned strands (Sentry et al., 2007). These current systems, although they provide rugged tendons with readily available hardware, are susceptible to corrosive attack from aggressive environments. Current permanent ground anchor strands require the use of double corrosion protection systems encapsulating the steel strands, to ensure a serviceable design life.

Technological advancements for civil construction applications has enabled new products such as glass fibre (GFRP) and carbon fibre (CFRP) reinforced polymers to pave the way for research into further improvements to the currently favoured steel tendon ground anchor system. Where steel reinforcement has been restricted due to aggressive ground conditions, minimal alternatives have been available for industry use until Fibre Reinforced Polymer (FRP) reinforcement was developed and successfully used as a durable construction alternative. With limited long term behavioural knowledge, FRP has shown considerable performance benefits compared to conventional steel products when used in civil engineering applications. In regions of high salinity, FRP manufactured reinforcement has been successfully used as an alternative to steel reinforcement for applications such as bridge decks, beams and slabs (Bakis et al., 2002, Halvard et al., 2003). Although extensive research has been conducted on FRP's as a substitute for conventional steel reinforcement (Bakis et al., 2002), minimal knowledge on FRP limitations, including FRP behaviour over prolonged exposure to aggressive ground environments is known.

This paper looks into understanding the physical and tensile performance of CFRP strands when cured under extreme ground conditions in an unstressed and stressed state.

2 EXPERIMENTAL INVESTIGATION

Investigation into the durability effects of CFRP strands in aggressive ground environments was undertaken with the view of establishing the levels of corrosion protection required for CFRP strands when commercially used in high capacity permanent ground anchors applications particularly if exposed to alkaline or acidic groundwater conditions.

2.1 Materials and Experimental Procedures

2.1.1 Material Properties

Two different CFRP based strands were adopted for this investigation, namely, CFCC and HS25x2. The CFCC is a 15.2mm diameter 7 wires helically wound carbon fibre reinforced polymer using a modified epoxy resin in the matrix. The HS25x2 is a 25mm x 2 mm carbon fibre reinforced polymer flat strand using vinyl-ester based resin in the matrix and coated with sand particles. The material properties, as provided by the manufacturers, are given in Table1.

Table1: Properties of CFRP test specimens

Property	CFCC	HS25x2
Dimensions		
Width (mm)	-	25
Diameter (mm)	15.2	-
Nominal Thickness (mm)	-	2
Effective Cross Sectional Area (mm²)	113.6	32
Linear Weight (g/m)	226	97
Carbon Fibre		
Minimum fibre volume ratio	0.62	0.64
Density (g/cm3)	1.5	1.8
Tensile strength (MPa)	4200	4900
Elastic modulus (GPa)	240	78
Resin		
Type	modified epoxy	Vinylester
Density (g/cm3)	1.6 - 2.0	1.15
Tensile strength (MPa)	80	>55
Product		
Tensile strength (MPa)	2200	2500
Elastic modulus (GPa)	141	140

2.1.2 Aggressive groundwater solutions

Two aggressive and one neutral solution were used to replicate groundwater conditions. All aggressive solutions had a Total Dissolved Solids (TDS) concentration much greater than 1,000mg/L. The following solutions were used:
Acidic groundwater → $NaHSO_4$ + NaCl
Alkaline groundwater → $NaHCO_3$ + NaOH + NaCl
Neutral groundwater → H_2O
Note: = NaCl was 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 solution; a pH of 1.0 (±0.5) was maintained for the acidic solution; while the neutral solution had a pH of 7.0 (±0.5).

2.1.3 Sample Curing

Each CFRP specimen was fully immersed in different aggressive environments and placed into a temperature controlled curing tank either in an unstressed or stressed state. Samples were cured for a period of one, three and six months. Temperatures of 30^{O}C and 60^{O}C were chosen for unstressed samples and 60^{O}C was selected for stressed specimens for this phase of the research program. Specimen curing was in accordance with ACI 440.3R-04 (2004).

2.1.4 SEM analysis

Assessment on the degeneration of the external protective barrier can assist in understanding absorption rates and the effects this may have on the specimens overall tensile performance. Samples from the cured specimens were obtained and mounted in a neutral epoxy resin. The prepared surfaces were then coated and analysed at the Monash University's Centre for Electron Microscopy (MCEM) using a scanning electron microscope. Electron back scatter diffraction was used to visually assess physical alterations to the CFRP strands as a result of curing and quantitative analytical spectroscopy was implemented to assess the depth of penetration of chemicals present in the aggressive ground solutions to which each specimen was exposed to during curing.

2.1.5 Tensile Capacity

Unstressed samples were placed into fully sealed HPVC cylinders (filled with respective solutions) and then suspended within the temperature controlled water tank. 3 specimens were tested in each solution over each temperature range.

Stressed specimens were placed into a special stressing frame whereby the stressed strand was housed within a HPVC cylinder. Each specimen was individually stressed to 50% ultimate load and locked off. Aggressive solutions were then added into the HPVC cylinder and sealed. Calibrated strain gauges were mounted to the strand to monitor relaxation effects during curing, enabling re-stressing of strands when required. Stressed samples were then suspended with the temperature controlled water tank.

Once both the unstressed and stressed samples have cured, samples were then removed from the aggressive solutions, cleaned in accordance with ACI440.3R-04 (2004) and prepared for ultimate tensile testing.

The tensile capacity assessment was carried out in accordance with ASTM D3039M (2000), ASTM D3916 (2002) and ACI440.3R-04 (2004). A range between 1000 and 3000 micro strain was used to establish the elastic modulus of each sample post curing as recommended by ACI440.3R-04 (2004). The accuracy of this investigation was calculated to two standard deviations at the 95% probability level. Ultimate tensile testing was conducted using the Baldwin testing machine, calibrated and serviced by Monash University.

3 RESULTS AND DISCUSSION

3.1 SEM Analysis

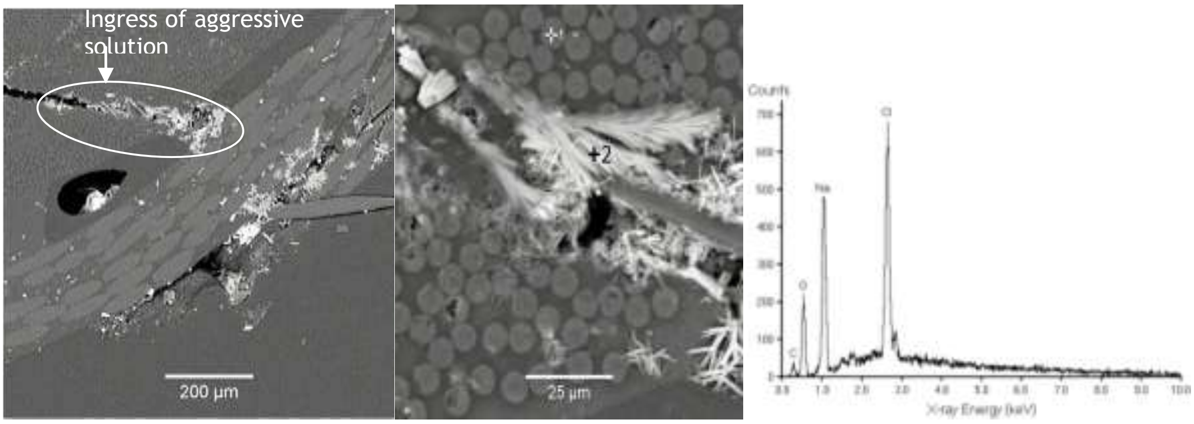
Scanning Electron Microscopy (SEM) analysis was carried out to develop a visual understanding between absorption rate and changes in ultimate tensile strength of CFRP materials

3.1.1 Unstressed Samples

For CFCC specimens cured in a neutral and acidic solution over a 6 month period at both elevated temperatures, no physical change in fibre/matrix composite was observed through SEM analysis. For samples cured in alkaline solution, localised ingress of the solution was observed over time. Figure 1a showed the aggressive solution residue had penetrated into micro-weak zones within the carbon fibre tows. This was observed over both temperature ranges. **Error! Reference source not found.** Figure 1b shows the crystalline structure of the deposited sediment. No signs of a change in either the physical shape or material properties of the carbon fibres were observed (Figure 1c).

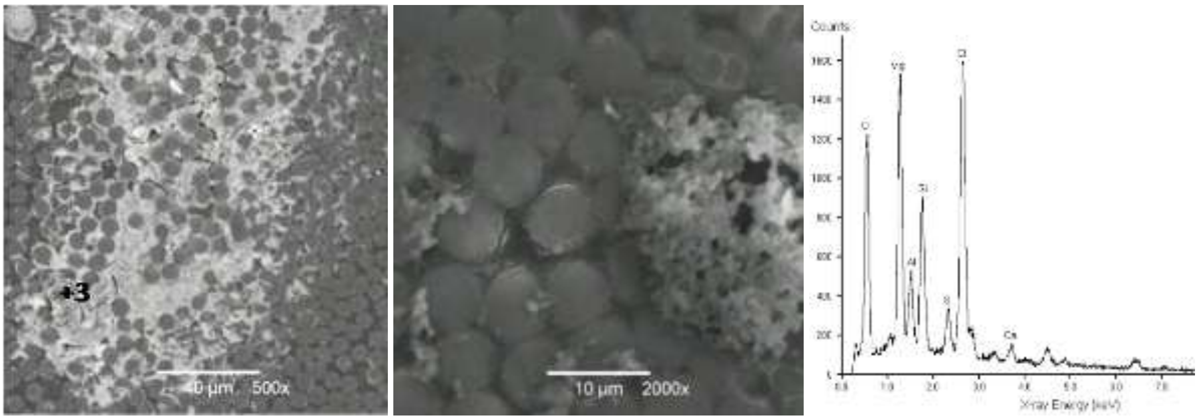
HS25x2 samples cured in neutral solution over 6 months at both temperatures showed signs of temperature fatigue. Localised micro cracks around the perimeter were evident with specimens cured after one month. HS25x2 samples cured in acidic and alkaline aggressive groundwater showed signs after just one month curing (at both elevated temperatures) of penetration of the aggressive solution into the body of the samples. Figure 2 depicts the general trends observed. As samples cured in the aggressive solution, penetration of the solution into the body of the sample progressed. Internal micro cracking which was observed and the resulting spectrum analysis are presented in Figure 2a and c.

The observation of the deposited aggressive groundwater sediment concurs with absorption results. Figure 2b shows the structure of the aggressive residue deposited as a result of exposure to the aggressive solution. It can also be see that there is evidence of vinyl-ester resin break down as a result of exposure to the aggressive solution.



(a) (b) (c)

Figure 1: CFCC strand cured at 30^{O}C and 60^{O}C in alkaline solution (a & b) 6 month specimen – evidence of aggressive solution residue penetrated into the carbon fibres; (c) Spectrum analysis point No. 2 (on fig 1.b)– sediments of the aggressive solution (Sodium and Chloride)



(a) (b) (c)

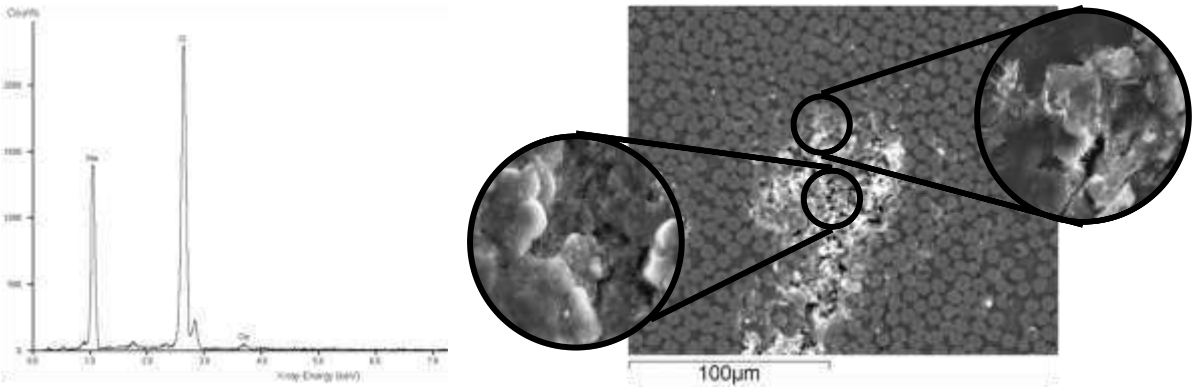
Figure 2: HS25x2 samples cured in acidic groundwater solution at 30^{O}C and 60^{O}C up to 6 months: (a) 3 month sample (60^{O}C;) (b) 6 month sample (60^{O}C); (c) Spectrum analysis from (a) point No. 3 (on fig 2a)- residue from acidic aggressive groundwater (and known contaminants due to sample preparation evident) deposited on and within the sample body).

3.1.2 Stressed Samples

As a consequence of the curing process, HS25x2 samples taken for SEM analysis had been damaged beyond use as a result of gripping issues. This indicates that curing these specimens in any solution at elevated temperatures affects the bonding between the fibres and the adjacent bond interface. This is an important issue which requires further research to ascertain reasons for this problem and identify product solutions. Additional assessments need to be carried out on CFRP-02 specimens once sustained gripping issues are resolved.

CFCC samples cured in neutral and acidic solutions showed no signs of fibre fatigue, damage, fibre splitting or de-bonding with the surrounding matrix after sample exposure to the solutions under stressed conditions. No signs of deposit penetration were observed from the visual SEM analysis.

CFCC samples cured in alkaline solution showed localised micro-cracks of the outer fibre layer had enabled the penetration along micro-cracks of deposits from the aggressive groundwater solution. Close inspection of the deposit exposed some minor deterioration of the bond between the epoxy and fibres (*Figure 3*b) and concentrations of sodium-chloride crystals (*Figure 3*c). Spectroscopy analysis conducted on the localised outer fibre layer micro-cracks (*Figure **3**a*) showed high concentration levels of sodium and chloride and minor concentrations of calcium. Although penetration of the aggressive alkaline solution occurred, no sign of fibre deterioration was evident.



(a) (b) (c)

Figure 3: Stressed CFCC samples cured at 60°C for 6 months (a) Spectrum analysis after 6 months; (b) deterioration of inner fibre region; (c) deposit within inner fibre region

3.2 Tensile Test Analysis

3.2.1 Unstressed Samples

HS25x2 samples recorded various modes of failure ranging between slippage at the gripping system due to gripping issues (at large loads) or as a result of deterioration in product performance due to specimen curing, shearing near the anchored end, longitudinal splitting of the samples or explosive failures (similar to that observed with other CFRP products). Over 6 months curing, it was observed that the ultimate tensile performance for HS25x2 increased marginally for specimens cured in neutral and aggressive alkaline solution, at 30^{O}C, but decreased in strength when cured in aggressive acidic solution. When compared to the tensile performance of HS25x2 over 6 months at curing temperature of 60^{O}C, both samples cured in aggressive alkaline and acidic solutions had a strength reduction, while the neutrally cured specimens marginally increased their strength.

There was minimal strength behavioural change of the ultimate tensile capacity of the CFCC specimens cured at 30^{O}C and 60^{O}C in the three solutions. The strength increase observed for this material type can be related to the potential strength hardening of the composite matrix as a result of elevated temperature curing.

Failure for CFCC samples were consistently explosive failures.

3.2.2 Stressed Samples

Due to the flat profile of the HS25x2 specimen, consistent issues with gripping during testing resulted in inconsistent findings. Further investigations are being carried out to determine an effective gripping system to repeat these tests.

Visual inspections of CFCC strand failure locations identified no consistent failure pattern for all specimens tested cured for six months in all curing environments. Failure was by rupture, located within the gauge length. Failure strains cured in acidic, alkaline groundwater and neutral solutions indicated minimal variation compared to control results (Figure 4).

4 CONCLUSION

SEM and Tensile capacity assessment in unstressed states of HS25x2 samples exposed to elevated temperatures were found to be affected by the exposure to the aggressive environments with reductions in tensile performance and visual observations of cracking and deterioration of the samples. CFCC samples although observing aggressive solution egress along micro-cracking showed minor strength increases as a result of strength hardening of the composite matrix. Explosive failure remains a feature of this material.

Tensile capacity and SEM assessment of CFCC under stressed conditions at elevated temperatures in aggressive environments over a six month period did not show signs of tensile strength decrease as a result of the accelerated curing process even though SEM analysis indicated penetration of aggressive solution had occurred after six months curing. Due to gripping issues, no reliable results were obtained for the HS25x2 samples. Further research into a reliable gripping system for the flat tendon is required prior to re-assessing the performance of this product under accelerated aggressive stressed conditions.

These works suggest that with careful selection of appropriate CFRP products, exposure to aggressive environments may not negatively impact on the tensile strength.

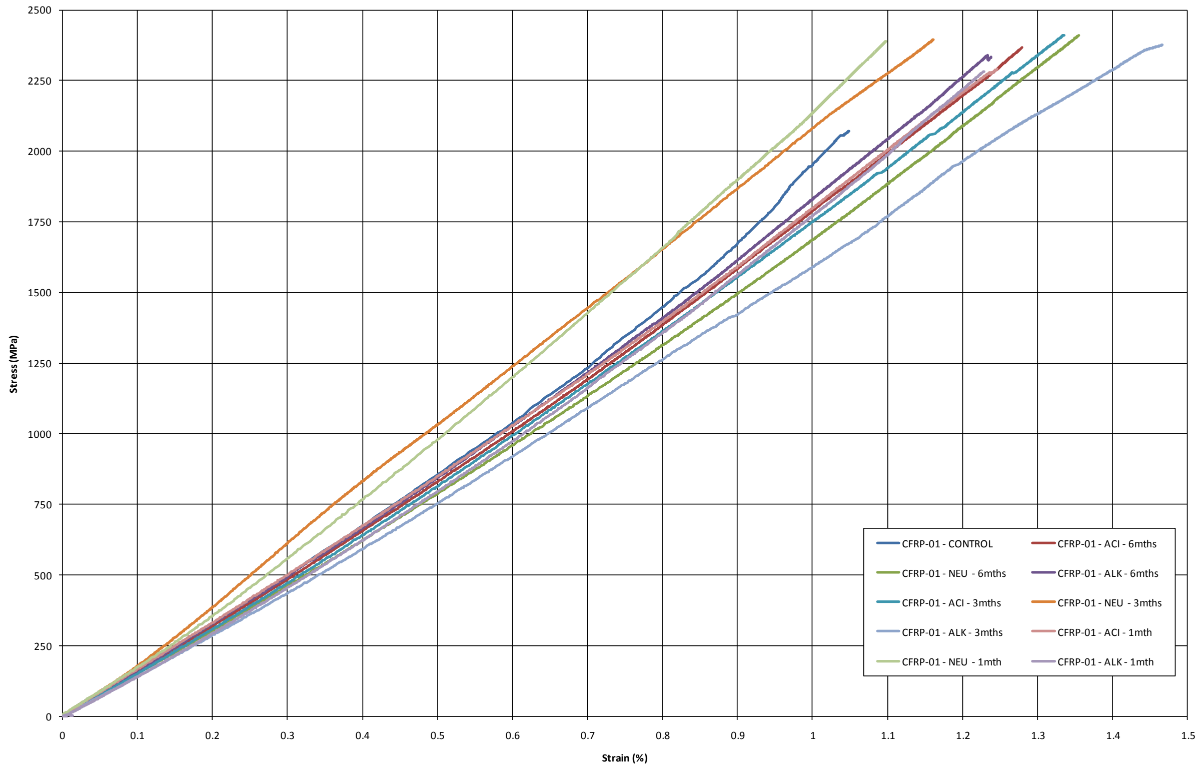


Figure 4: Tensile test results of stressed CFCC samples.

5 ACKNOWLEDGEMENTS

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