Durability of Carbon Fibre Reinforced Polymer (CFRP) strand for use in high capacity permanent ground anchors

M. Sentry[1], A. Bouazza[1], R. Al-Mahaidi[1], F. Collins[1], L. Carrigan[2], D. Loidl[2], C. Bluff[2]

[1] Monash University, Melbourne, VIC, Australia

[2] Geotech Pty Ltd, Tullamarine, VIC, Australia

ABSTRACT

Steel strand ground anchors 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 times, FRP reinforcement has been successfully researched and used as a durable construction alternative to steel. Minimal research has been devoted to developing FRP strands for use in high capacity ground anchors. The paper summarises current research knowledge, best practices for use of CFRP strands in ground anchor systems and an interim report on CFRP strand durability performance in comparison to steel strands, when exposed to extreme aggressive environments over time at accelerated temperature in both stressed and unstressed state.

1. Introduction and Background

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

Technological advancements of fibre reinforced polymer (FRP) products for applications in civil construction have allowed new products such as glass fibre (GFRP), aramid fibre (AFRP) and carbon fibre (CFRP) to pave the way for research into further improvements to the currently favoured steel tendon ground anchor system.

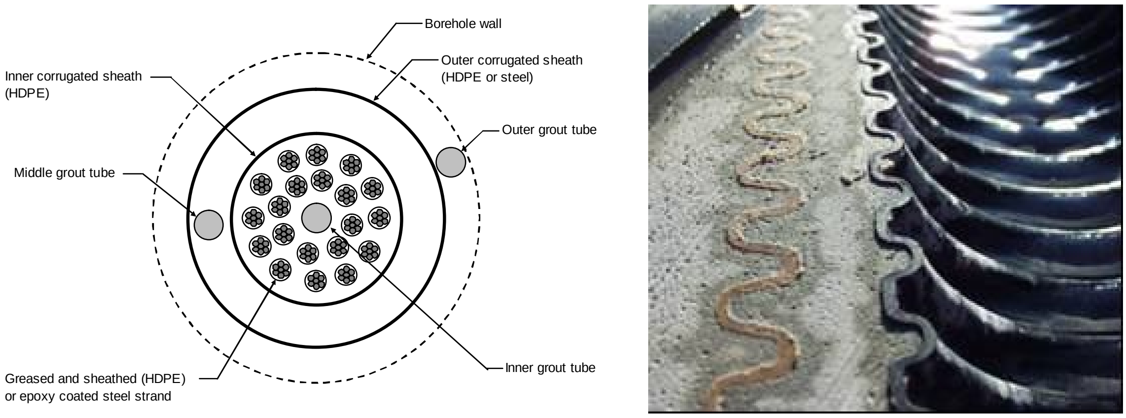
FRP’s are characterised by their superior resistance to aggressive environments, compared to steel. Where steel reinforcement has been restricted due to aggressive ground conditions, minimal alternatives have been available for industry use until FRP reinforcement was developed and successfully used 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 stressed.

2. 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 (Littlejohn and Bruce, 1977).

To eliminate risk of corrosion, international standards including EN1537, 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 (Sentry et al., 2007b).

Littlejohn (Littlejohn, 1987) reported 35 known cases of corrosion related failures to steel tendon ground anchors, concluding that free length corrosion comprised 60% of failures, whilst 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 resulted from inadequate grout placement.



(a) (b)

Figure 1: (a) Schematic of double protection system for permanent ground anchor (Sentry et al., 2007b); (b) longitudinal section - double corrosion protection through the bond length of a ground anchor (Mothersille, 2006).

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 (Weerasinghe and Adams, 1997). 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 (1997) and Mothersille (2006) provide examples where corrosion occurred above and below the anchor head, resulting in anchor strength reduction (Figure 2).

(a) (b) (c)

Figure 2: Failure of anchored quay wall (b) corroded barrels and wedges in anchor head (c) lack of corrosion protection behind anchor block (Mothersille, 2006)

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

3. Advancements in corrosion resistant materials – FRP

Current complexities of double corrosion protection has shifted research into investigating the use of alternative materials to assist in minimising risk of anchor failure due to corrosion, including investigations into the use of fibre reinforced polymers (FRP).

3.1 Fibre reinforced polymer (FRP) materials

FRP consists of a group of materials containing 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 (Zhang et al., 2000). North America is continuously developing and refining the use of inorganic filaments as a substitute for steel in concrete reinforced structures (Tardif et al., 2007, Van der Wal and Boulfiza, 2007).

FRP filaments consist of various kinds of load bearing fibres of high tensile strength and high modulus of elasticity. Ultimate tensile strengths of carbon fibre reinforced polymer (CFRP) filaments range from 290 to 758GPa and aramid fibre reinforced polymer (AFRP) filaments ranges from 70 to 179GPa. Prestressed steel, by comparison, has tensile a strength of 195GPa (Zhang and Benmokrane, 2004).

For all FRP materials, a polymer matrix is used to bond the fibres, protect them against environmental effects whilst assisting 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 a FRP composite material. Thermoset polymers including epoxy, polyester and vinyl ester are preferred resins for FRP material in civil engineering applications (Zhang and Benmokrane, 2005).

3.2 Properties of FRP Composites

Composite products currently able to provide the industry with an environmentally resistant alternative product to steel tendons for ground anchor applications include glass fibre (GFRP), aramid fibre (AFRP) and carbon fibre (CFRP) reinforced polymers. FRP properties can vary depending on quality, manufacturer and manufacturing process (Table 1).

Table 1: Properties of FRP composites (after Zhang and Benmokrane, 2005)

Property	**GFRP**	**AFRP**	**CFRP**
Minimum fibre volume ratio	0.55	0.6	0.63
Density (g/cm^3)	2.1	1.38	1.58
Longitudinal tensile strength (MPa)	1080	1280	2280
Transverse tensile strength (MPa)	39	30	57
Longnitudinal modulus (GPa)	39	78	142
Transverse modulus (GPa)	8.6	5.5	10.3
In-plane shear strength (GPa)	89	49	71
In-plane shear modulus (GPa)	3.8	2.2	7.2
Major Poisson's ratio	0.28	0.34	0.27
Maximum longitudinal strain (%)	2.8	1.5	1.5
Maximum transverse strain (%)	0.5	0.5	0.6
Relaxation ratio (%)			2-3

FRP composites are known to have a brittle mode of failure compared to yielding failure of steel (Figure 3) (Benmokrane et al., 2002). Designers need to consider the brittle failure nature of FRP composites when designing.

Tensile strength is dependant on length of tendon, the anchorage system being used and the loading rate. CFRP ranges between 13-18% higher tensile strength than steel (Zhang and Benmokrane, 2005). The brittle nature of FRP composites results in the modulus of elasticity for CFRP and AFRP composites to be in the order of 30% and 65% lower respectively, than prestressing steel (Zhang and Benmokrane, 2005). Tensile strain, at failure, of CFRP ranges between 1.3-1.6% and AFRP ranges between 2.0-3.7%, compared to 6% for prestressing steel.

FRP fibres are weak in transverse loading. FRP shear strength is dependent on the matrix used to construct the composite, which is considerably lower than its tensile strength. Santoh (1993) compared AFRP, CFRP and prestressing steel showing lateral shear strengths of 11% (CFRP), 15% (AFRP) and 47% (prestressing steel) of the respective tensile strength. FRP (CFRP and AFRP in particular) density is approximately 15-20% that of prestressing steel (Benmokrane et al., 1997).

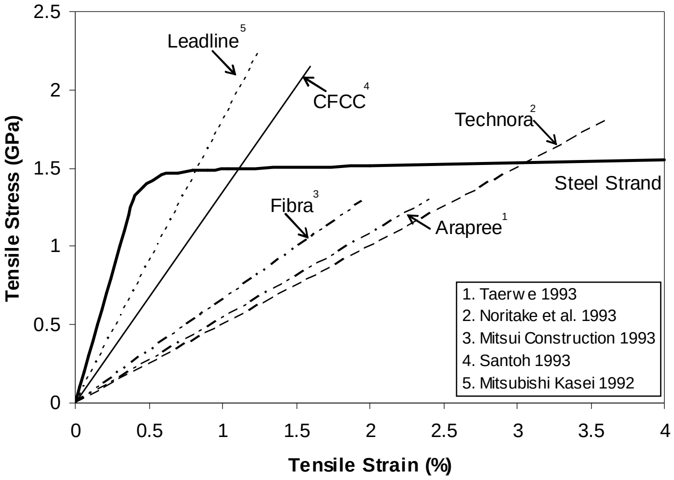


Figure 3: Typical tensile stress-strain behaviour of various FRP products compared to steel strand (after Benmokrane et al., 1997)

FRP creep rupture may be more prominent than in steel strand due to brittle failure of FRP tendons over time under sustained loading or under adverse conditions (Benmokrane et al., 1997, Zhang and Benmokrane, 2005). Under initial stress of 65%f_{pu}, creep strain of CFRP tendons is approximately 0.007% after 100 years (Benmokrane et al., 1997). Zhang et al. (2005) reported that the relaxation for AFRP was 12% after 1000 hours (under load of 0.6f_{pu}), while CFRP ranged between 0.48% and 0.96% (0.5f_{pu} – 0.8f_{pu}) when compared to prestressing steel relaxation rate of 1.02% to 7.35% (0.5f_{pu} – 0.8f_{pu}).

3.3 FRP composite ground anchorage design

FRP tendon ground anchors must consider the same design criterion and procedures as conventional steel tendon ground anchors. Several quality standards are available to assist designing with FRP tendons. In addition to standards, government organisations have established rigorous guidelines complementing local and international standards. Adjustments to current standards and guidelines are required when replacing steel tendons with FRP tendons. Current documentation relevant to ground anchorage construction and for application of FRP tendons in ground anchors include (but are not limited to) EN 1537:2002–Execution of special geotechnical works–Ground Anchors; BS 8081:1989–Ground Anchorages; ACI 440.4R-04-Prestressing Concrete Structures with FRP

Tendons; CAN/CSA S806–Design and Construction of Building Components with Reinforced Polymers; ISIS Canada-Educational Modules No. 1– 8; Post Tensioning Institute (USA)-Recommendations for Prestressed Rock and Soil Anchors and RTA QA Specification B114 Ed 2/Rev 3 1999.

4. 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, groundwater flow path or introduced agents. 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 ongoing experimental analysis investigating the durability of various CFRP strand materials exposed to two different aggressive groundwater conditions, and a neutral condition, at various temperatures under unstressed and stressed conditions. This investigation aims to establish what levels of corrosion protection, if any, are required for high capacity ground anchorage systems using CFRP strand.

4.1 Factors affecting CFRP durability

Steel is deemed isotropic and homogenous, whilst CFRP materials by comparison are anisotropic and heterogenous. Behaviour of the bond between the steel and the cementitious product in conventional steel reinforced concrete is generally influenced by the concrete strength (Nanni et al., 1998). On the other hand, FRP bond behaviour in FRP reinforced concrete products is influenced by numerous factors as indicated by Nanni et al. (1998) including; fibre type, matrix type, FRP geometry, and FRP manufacturing process.

Micelli and Nanni (2004) performed experiments to investigate the durability of FRP reinforcement bars in concrete structures, indicating various damage mechanisms for FRP reinforcement. These must be considered relevant to ground anchors and include; fluid absorption and influence on physical/mechanical properties, creep and stress relaxation, mechanical fatigue and environmental fatigue damage and weathering. Those mechanisms acting as a result of attack by external agents, relevant to a ground anchor system, include moisture and aggressive solutions (within groundwater), alkaline environment (within both the grout and groundwater), and fatigue loads (from superstructure).

Micelli and Nanni (2004) suggest that the rate of degradation of polymer composites, exposed to a fluid environment is related to the rate of absorption 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 their polymer composition, FRP’s are classified as a viscoelastic material and can exhibit creep and stress relaxation to greater extents than steel reinforcements.

4.2 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. Groundwater characteristics can be determined by factors such as the presence of contaminants due to soil/rock condition, mineralogy of the surrounding ground, or environmental factors caused by human intervention (mining, industrial leakage, etc) all has a part in providing a certain quality to the groundwater. Aggressive groundwater is commonly understood as water which is either acidic or alkaline. The various ion levels present and the total dissolved solids (TDS) determine the aggressiveness of the 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^-) (Walton, 1970). AS3600 exposure classification recommends that any soil with a pH<4.0 or with groundwater>1000mg/L of Sulphate shall be deemed aggressive. Walton (1970) concluded that any groundwater environment can be deemed aggressive should the TDS exceed 1000mg/L and be comprised of one or more of the above mentioned minerals.

Acidic aggressive groundwater in Australia is commonly located in soils with groundwater close to the surface or near costal regions where Sulphate levels are excessive (Carse, 2004). Sodium Hydrogen Sulphate ($NaHSO_4$) is a common solution found in highly acidic groundwater where Sulphate is present.
1HEQR-D7D8S-253SJ-Y09TM
Although AS3600 and EN1537 do not refer to alkaline aggressive groundwater, it is essential that this study investigates these effects on FRP. Numerous studies involving extremely alkaline concrete pore water have been carried out on many forms of FRP products. No test to date has investigated the effects alkaline aggressive groundwater has on FRP products, in particular CFRP. Extreme alkaline groundwater's pH ranges between 8.0 – 10.0. It is the ion combination which can be present in Australia's aggressive groundwater that can have different detrimental effects on steel properties compared with those 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>8.5. These extreme alkaline groundwater conditions are associated with the inclusion of Sodium Bicarbonate ($NaHCO_3$) (Walton, 1970). 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 (Walton, 1970).

4.3 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 (Micelli and Nanni, 2004). Micelli and Nanni (2004) and ACI440.3R-04 method for analysing CFRP's rate of absorption (Equation 1) was used in this study

$$M_t(\%) = \frac{W - W_d}{W_d} \times 100 \qquad (1)$$

W = moist weight; W_d = dry weight at time t=0

5. Investigation into the durability of CFRP strand in aggressive ground

An ongoing investigation into the durability effects of CFRP strands in aggressive ground environments is being undertaken at Monash University. This research is determining what level of corrosion protection is required for CFRP strands when commercially used in high capacity permanent ground anchors if exposed to alkaline or acidic groundwater conditions.

This paper is a progress report for samples exposed to aggressive solutions at an elevated temperature of 60^{O}C in an unstressed state over a one and three month period.

5.1 Experimental procedure

5.1.1 Tensile capacity assessment

The experiment investigates what effect acidic and alkaline aggressive groundwater may have on the ultimate tensile performance of CFRP strands. Two CFRP based strands were used in this investigation, CFCC (Tokyo Rope – Japan) and HS25x2 (Sireg – Italy). Each specimen is fully immersed in different aggressive environments and placed into a temperature controlled curing tank. Curing of the specimens is over a one, three and six month period. Temperatures of 30^{O}C and 60^{O}C were chosen. The specimens endure these conditions under an unstressed and stressed state. This paper presents results only for a 60^{O}C temperature over one and three months in an unstressed state.

Specimen curing is in accordance with ACI 440.3R-04. Method of assessment is in accordance with ASTM D3039M, ASTM D3916 and ACI440.3R-04. Method of determining elastic modulus of the cured specimens is in accordance with ACI440.3R-04. An elastic modulus range of between 1000 and 3000 microstrain is recommended for use. The accuracy of this investigation is 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.

All specimens are compared and an assessment of the materials ultimate tensile strength performance using Arrhenius modelling can be used to establish the levels of long term corrosion protection required for CFRP strands being used for permanent ground anchors.

5.1.2 Rate of absorption

CFRP absorption analysis is carried out on all specimens in line with Micelli and Nanni (2004) method of analysis (Equation 1). Specimens were measured and weighed prior to curing and again post curing. Visual, weight and scanning electron miscrope (SEM) are the methods used to assess rates of absorption and changes to materials.

SEM analysis is an excellent tool providing a detailed micro-view of how absorption can occur and what effects this might have on the specimens overall tensile performance.

5.2 Aggressive groundwater solutions

Two aggressive solutions and one neutral solution are used to replicate groundwater conditions in this investigation. All aggressive solutions had a minimum TDS concentration >1,000mg/L. The following solutions are being used:

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

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, while a pH of 1.0 (±0.5) was maintained for the acidic groundwater solution. The neutral solution had a pH of 7.0 (±0.5).

5.3 Material properties

Two different CFRP based strands are currently being adopted for this research investigation; CFCC from Tokyo Rope (Japan) and HS25x2 from Sireg (Italy). The manufactures material properties are as per **Error! Reference source not found.**.

Table 2: Technical properties for CFRP test specimens being used in research project (Tokyo Rope, 2006., Sireg, 2006.) and stress relieved steel strand (One Steel)

Property	CFCC (Tokyo Rope)	HS 25x2 (Sireg)
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

5.4 Results and discussion

5.4.1 Absorption of aggressive solution

Specimen weights were analysed prior to immersion into aggressive groundwater solutions at various temperatures and then re-weighed post curing. The absorption rate was analysed using Equation 1. Figure 4 illustrates the rates of absorption over the testing time frame.

The results clearly show that CFRP absorbs solution over time. From the limited results it is evident that rates of absorption increase for CFRP materials when exposed to aggressive groundwater compared to exposure to a neutral solution. HS25x2 CFRP strand has the highest rate of absorption. Absorption trends for all solution types indicate an increase in absorption over time.

CFRP rates of absorption are of interest at these elevated temperatures as it may allow for deterioration of fibre strength over time. SEM analysis can provide a greater understanding to how aggressive solution can penetrate the strand and investigate if there is any deterioration of the composite matrix as a result of absorption.

Preliminary SEM analysis (Figure 5) indicates that although there is a complete epoxy coating around the perimeter of the CFCC strand (Figure 5 (a) left side of image), void cracks within the composite matrix may result in variations to material strength over time (Figure 5 (b)).

Figure 5 (c) are images of the CFRP material HS25x2. The uncured samples clearly show the longitudinal fibre filaments with the epoxy coating surrounding the filaments. Gaps within these filaments pose a potential threat to solution ingress and potential attack.

SEM analysis on cured samples can provide more detail of the methods of absorption by CFRP specimens and if there is any relationship between aggressive solution attack and ultimate tensile failure modes.

Further analysis over long time frames must be conducted prior to drawing sound conclusions on the effects of absorption has on the overall tensile strengths of CFRP strands. This research is currently being undertaken at Monash University.

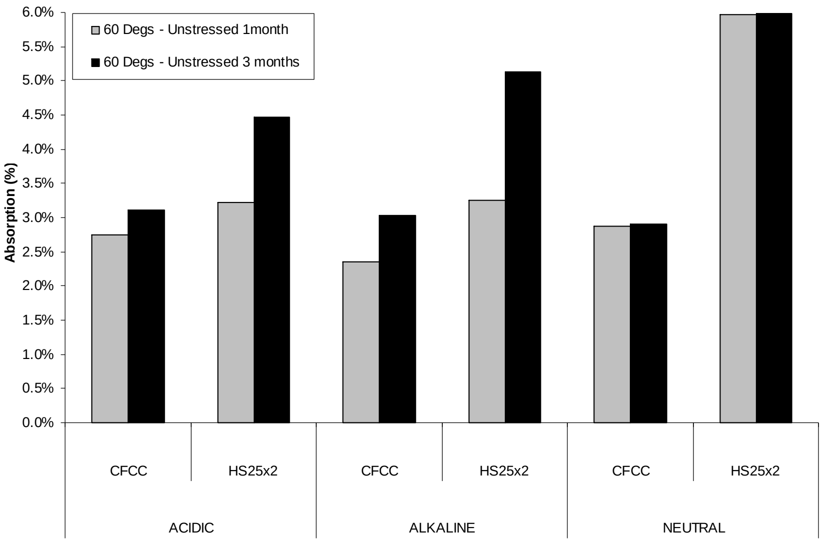
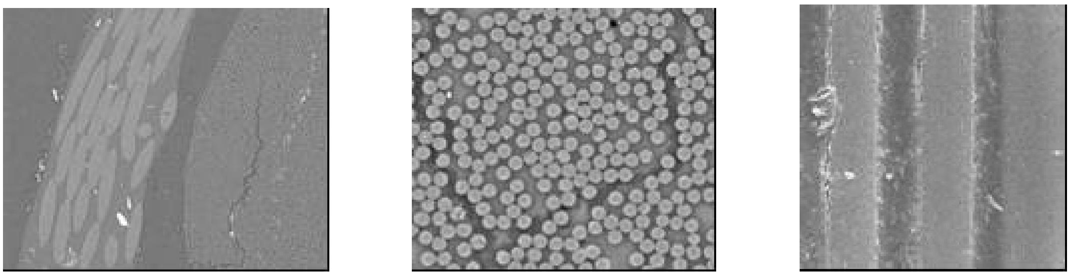


Figure 4: Absorption of specimens immersed in aggressive groundwater at elevated temperatures



(a) (b) (c)

Figure 5: SEM analysis on CFRp strand prior to immersion into aggressive groundwater solution (a) CFCC at 100x magnification (b) CFCC at 500x magnification (c) HS25x2 at 1000x magnification.

5.4.2 Ultimate durability tensile capacity of Steel and CFRP strands

The results from CFRP (CFCC) specimens curing in acidic and alkaline groundwater and a neutral solution over 0, 1 and 3 months at an elevated temperature of 60^{o}C in an unstressed state are reported in Figure 6 and Table 3.

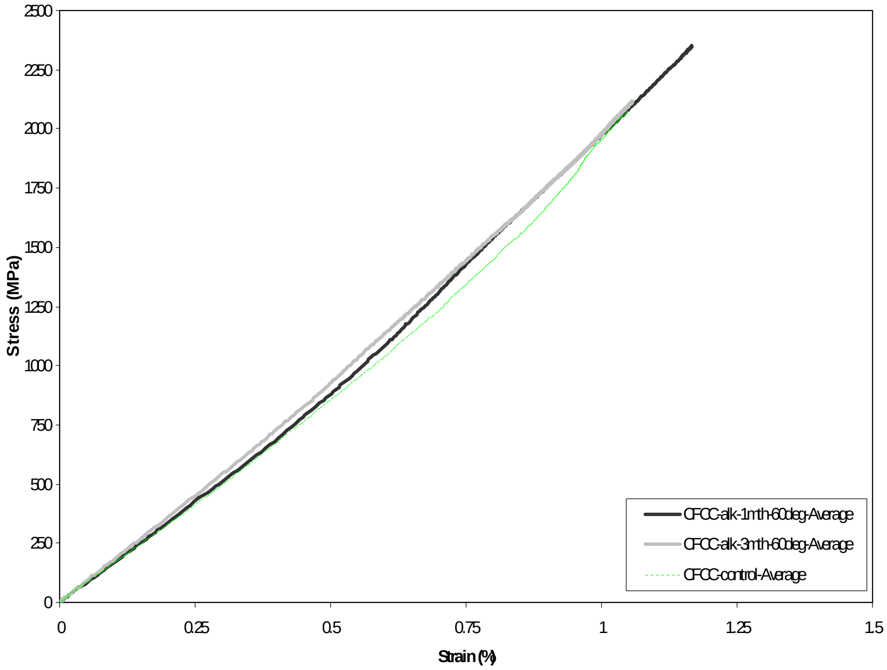
Results for the CFRP product HS25x2 for periods of 0, 1 and 3 months are currently inconclusive due to ongoing gripping issues. Results have been achieved but verifications must be conducted prior to specimen analysis and discussion. Further publications will present these results and comparisons

It is evident that even from these initial stages of this durability assessment, the minimal tensile changes when cured in the aggressive ground environments. It was observed that specimen strength initially increased within the first month, possibly due to the additional curing of the composite matrix at the elevated temperature of 60^{O}C.

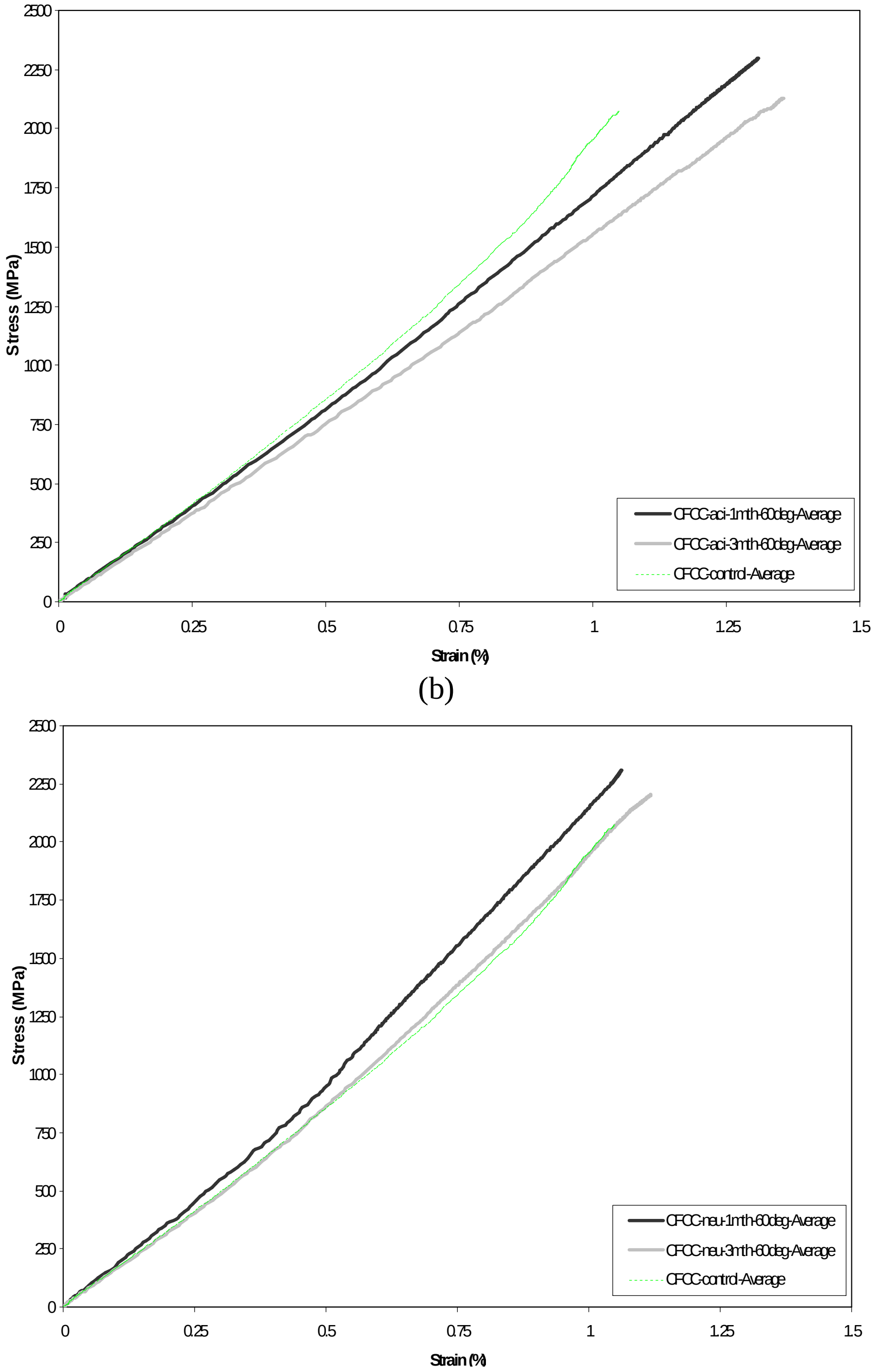
Strength increases of 11.5%, 13.5% and 10.9% were observed for the neutral, alkaline and acidic solutions respectfully. After three months, the specimen strength reduced, but still showed a strength increase from the control samples. An overall strength increase of 6.3%, 2.1% and 2.8% were observed for the neutral, alkaline and acidic solutions, after three months curing, respectfully. Further assessments on six month curing can provide greater knowledge on the strength effects of the cured specimens.

CFRP specimens showed minimal changes to the materials brittle nature when the specimens were maintained in a saturated state at elevated temperatures over time. Acidic solutions showed a decrease in elastic modulus over the three months period of 12% (6% decrease after 1 month). Alkaline solution showed an increase 7% after one month, but reduced to an increase of 5% between the control specimens and the 3month trial specimens. This showed only a 2% elastic modulus decrease from specimens curing from one to three months. CFCC specimens immersed in a neutral solution initially showed a 16% increase in elastic modulus after one month, however the elastic modulus reduced after three months to fall below the control specimens by 3%. This was a 16% change from one month results to three month results.

Although results showed changes in the materials elasticity over time, as visually indicated in Figure 6, there is minimal change over time between each series of specimens sampled. Specimens immersed in the neutral solution had an increase in ultimate failure strain of 6.6% over a three month period, with a 1.3% increase in ultimate failure strain after just one month. Acidic groundwater specimens exhibited major ultimate failure strain increases, with a failure strain increase of 24.9% after just one month and a total of 29.4% after three months. Specimens affiliated with alkaline groundwater exhibited a failure strain increase of 11.2% after one month, but only displayed a total failure strain of 0.8% after three months. This equates to a decrease in failure strain of 10.4% from the one month to the three month tests.



(a)



(b)

(c)

Figure 6: Unstressed stress-strain relationships of CFCC strand over 0, 1 and 3 months curing in various aggressive solutions at a curing temperature of 60^oC (a) CFCC curing in alkaline groundwater, (b) CFCC curing in acidic groundwater and (c) CFCC curing in neutral solution.

As indicated by Bakis et al., (2007) and Benmokrane et al., (2002) CFRP's tend to fail in a brittle manner. As such the composite matrix breaks down and exposes rough and jagged failure planes (Figure 7). Explosive failures were common for all types of CFCC strand. Strand failure generally occurred close to the proximal end of the bonded anchorage, but still within the test area.

These results in conjunction with the absorption of CFRP materials over time provides the authors an opportunity to further investigate whether a relationship between the absorption rates affect the strength, ductility and overall performance of CFRP strands once exposed to aggressive ground conditions in a passive state.

Table 3: Ultimate Stress and corresponding failure strain for CFCC specimens immersed in alkaline groundwater, neutral solution and acidic groundwater solution over a total period of three months (of a 6 month experiment).

Solution	Curing Time (months)	Elastic Modulus (GPa)	Failure Strain (%)
Control	0	170	1.05%
Neutral	1	197	1.06%
	3	164	1.12%
Alkaline	1	182	1.17%
	3	178	1.06%
Acidic	1	160	1.31%
	3	150	1.36%

Although these results are interesting to analyse, it is important to be able to study and compare how these specimens are able to perform when exposed in the aggressive ground environments over the extended six month period, both in these unstressed conditions and in a stressed condition.

(a) (b)

Figure 7: (a) & (b) CFCC (CFRP) strand, tensile tested to failure after 1 month exposure to acidic aggressive groundwater.

6. Future research works

This paper has primarily findings on one type of CFRP specimen in a range of CFRP materials currently under investigation in this experiment in an unstressed state at one elevated temperature range.

As indicated, the results reported herein are part of a progressive report on the durability and absorption effects of CFRP materials when exposed 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.

In addition to the durability assessment of CFRP materials for use as permanent ground anchorage systems with minimal corrosion protection, investigations is currently being undertaken on the bond effects of CFRP strands for use in high capacity ground anchors and finite element evaluation and modeling of CFRP stand, used as a high capacity ground anchors in rock. Full scale gunbarrel comparisons and model verifications are being investigated.

7. Conclusions

Although recent developments to conventional steel tendon ground anchors have improved corrosion protection, the implementation of FRP's into the construction industry provide a durable construction alternative.

This paper presented a progress report on a durability study, currently being conducted at Monash University, investigating effects of various aggressive groundwater solutions have on the tensile performance of numerous CFRP materials that can be utilised as a practical alternative to steel strands in ground anchorage systems. The completed investigation aims to be able to address the long term effects of corrosive solutions on CFRP materials and develop a means to establish what levels of protection is required when constructing CFRP based ground anchors.

Acknowledgements

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