Durability Assessment of Flax Fibre and Bio Epoxy Composites in Harsh Environmental Conditions

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Thesis
Submitted to Flinders University
for the degree of

Master of Engineering (Civil)

College of Science and Engineering
2024/06/06

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ABSTRACT

The study's main aim is to research the performance of flax fibre and bio epoxy composites under harsh environmental conditions when used as confinement material in construction. Synthetic fibres, such as carbon fibre, and synthetic epoxy resins have been well-researched and proven to provide strong performance gains in concrete members when used as composites. Natural fibres like flax fibres and natural epoxy are a promising eco-friendly and economical alternative. However, because of inconsistent fibre quality and degradation in harsh environments, they cannot be readily used in construction. In order to use natural fibres and bio epoxy as a replacement for synthetic fibres, an experimental study of such materials in different harsh environmental conditions needs to be done and appropriate treatment methods should be applied if needed. However, experimental testing and study on natural fibres are limited, indicating the need for extensive study in this area.

In this study, the amount of performance loss in flax fibre and bio epoxy composites due to exposure to saltwater and high ambient temperature was studied through experimental testing. The effect of salt water and high ambient temperature for different lengths of time were compared with each other and finally compared with control samples not exposed to harsh environments. The experiment was undertaken in the lab by moulding concrete cylindrical specimens. Then, the unidirectional flax fibre sheet was wrapped in a hoop direction around the concrete cylinders with the use of bio-epoxy resin. The wrapped cylinders were then placed in a corrosion chamber and oven to simulate the corrosive environment of marine conditions and high ambient temperatures for 3, 7, 14 and 28 days. Compressive strength test was carried out on each sample and the results thus obtained for each sample were compared and evaluated. The degradation in performance of each sample exposed to harsh environmental conditions for different lengths of time is presented and discussed in this report. The amount of performance decline because of different harsh environmental conditions for different lengths of time was quantified. The Research was undertaken between September 2023 and June 2024 at Flinders University, College of Science of Engineering Laboratory located in South Australia, Australia.

Confinement of concrete cylinders using flax fibres and bio epoxy composite resulted in significant increases in compressive strength by up to 85%. Exposure of composite samples to saltwater for 28 days duration resulted in a minimal decrease in the ultimate strength of samples indicating the strong potential of such composites in construction applications. Exposure of samples to high heat of 80 degrees Celsius showed some gain in compressive strength, possibly because of the curing effect of bio epoxy, which could be advantageous in certain construction scenarios where heat resistance is required.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university.
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

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I certify that I have read this thesis. In my opinion, [✓ it is]/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering (Civil). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/[✓ fully] (please circle).

Signature of Principal Supervisor...

Print name of Principal Supervisor...Thomas Vincent...

Date...5/6/2024...

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my academic supervisor, Dr Thomas Vincent, for his constant support and helpful advice during my research project. His guidance has been incredibly helpful throughout this entire journey.

I would like to extend my thanks to Zakir Ikhlasi for his guidance and enthusiasm, which greatly contributed to the success of this project.

I am equally grateful to Mr. Tim Hodge, Senior Technical Officer, and Mr. Westley Penney, the Civil Technical Support Officer for their invaluable assistance in carrying out the experimental works.

My appreciation also goes to Issa, Liam and Emily, my fellow researchers for their assistance during planning and experimental works. Their help not only made the project easier but also more enjoyable, turning challenging tasks into rewarding experiences.

Finally, I am profoundly grateful to my family and friends for their unwavering support and encouragement throughout my academic journey. Their belief in me has been a constant source of motivation.

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1. INTRODUCTION

1.1 Background

Fibre Reinforced Polymer (FRP) Composites are a rapidly emerging practice in the building industry that are used to increase the strength of a new structure and in retrofitting of partially damaged concrete structures (Mohammed, et al., 2019). The majority of the time, FRP composites are used to strengthen/rehabilitate the existing structure of concrete, timber, and steel. FRP composites are also commonly being used in the construction of new structures either as confinement material in circular columns and piles or as substitutes for steel reinforcement bars (Mohammed, et al., 2019). The two synthetic fibres that are most frequently utilized in construction as fibre-reinforced polymer composite materials are glass fibres and carbon fibres.

Using synthetic fibres as construction material comes with both benefits and drawbacks. The key benefits of synthetic fibres are high tensile strength, high strength-to-weight ratio, lightweight nature, and ease of usage, which is why fibre composites made up of synthetic fibres are becoming more and more popular (Kobets & Deev, 1997). However, as carbon fibres and other synthetic fibres are made from polymers derived from petroleum-based products, they have a high carbon footprint and thus release large quantities of carbon dioxide (greenhouse gas) into the atmosphere (Ramachandran, et al., 2023). Thus, these fibres are harmful to both human health and the environment. Due to these drawbacks shown by synthetic fibres, natural fibre alternatives like jute and flax have gained popularity among researchers recently.

Natural fibres have several benefits over synthetic fibres, including biodegradability, affordability, eco-friendliness, and sustainability (Joshi, et al., 2003). Natural fibres (jute fibres and flax fibres) are proven to have high tensile strength, thus, showing great potential for use in the construction industry as confinement material replacing synthetic fibres (Sen & Reddy, 2011). Although natural fibres have great potential to replace synthetic fibres in construction, they are not in a position to be used in their natural state because of durability and inconsistency issues when used in harsh environmental conditions. Natural fibres tend to deteriorate while used in wet conditions and other harsh environmental conditions like the presence of salt water. In wet conditions, natural fibres show swelling by absorbing moisture and exhibit different mechanical properties (tensile strength, strain, and so on) as compared to dry conditions (Stamboulis, et al., 2001). Therefore, natural fibres should be made resilient to degradation in order to be used as a substitute for synthetic fibres.

1.2 Area of Research

In this study, salt water and high ambient temperatures will be used to create harsh environmental conditions, and the behaviour of natural fibre composites will be examined in a lab setting. The degree of harm caused by such an environment for various lengths of time to natural fibre composites will be assessed. The subject of this study will be the flax fibre and bio epoxy composite, and the test parameters will be exposure duration, plus different environmental conditions. Flax fibre is a commonly used fibre material in industrial use that is produced by processing the stem of a flax plant and is available commercially in different forms of products such as woven fabrics, unidirectional tape, and other forms.

The result of the experimentation will be useful in the assessment of the performance of flax fibre composites in different environmental conditions when used as construction material. Results will help decide whether or not to use the flax fibre composites in the environmental conditions tested in this study. The findings of this study will also help understand and quantify the degradation of natural fibres so future research can then develop targeted treatment methods. If natural fibres and bio epoxy can be used successfully as the replacement of synthetic fibres and epoxy as construction material in the confinement of concrete structures, the cost associated with synthetic fibres will be minimized, while simultaneously lowering the environmental impacts shown by synthetic fibres.

1.3 Project Objectives

The main objective of the project was to study the behaviour of concrete cylinders confined with flax fibres, subjected to axial compressive load. Also, the performance of flax fibre and bio epoxy composites under harsh environmental conditions including salt water and high heat was studied. The main objectives of this research are listed below.

- Analyse the confinement behaviour of flax fibre and bio epoxy composite on concrete cylinders subjected to compressive load.
- Analyse the performance of flax fibre and bio epoxy composite under saltwater spray and high heat conditions.
- Compare the strength of flax fibre bio epoxy composite samples subjected to corrosion with control samples.
- Compare the strength of flax fibre bio epoxy composite samples subjected to salt and moisture for varying duration of time.
- Assess the suitability of bio epoxy when used with flax fibres in the conditions mentioned.

2. LITERATURE REVIEW

2.1 Use of Synthetic Fibres in Construction

FRP Composites made up of synthetic fibres and epoxy resin are being used in new construction as well as in the recovery or strengthening of old concrete structures. In the case of new structures, FRP composites are being used as reinforcement bars replacing steel reinforcement bars (Jabbar & Farid, 2018). FRP composites are used also in the form of confinement materials in the construction of circular columns and piles (Hollaway & Teng, 2008), (Erp, et al., 2005). FRP composites are however more commonly used in the rehabilitation or retrofitting of existing concrete structures like bridges and buildings. Rehabilitation of concrete structures that are partially damaged during events like earthquakes can also be achieved by the use of FRP composites (Hollaway & Teng, 2008). Thus, it has been demonstrated that FRP is a more practical substitute for traditional materials like steel and concrete.

The most popular synthetic fibres that are utilized in composite structures are glass fibres and carbon fibres. Synthetic fibres are known to have very high tensile strength. The tensile strength of carbon fibres can reach as high as 8000 MPa (Kobets & Deev, 1997). Compared to steel, carbon fibres are extremely lightweight and thus have a very high strength-to-weight ratio (Kobets & Deev, 1997). When compared to steel and concrete, carbon fibre and other synthetic fibres are more resistant to chemical deterioration due to their inert nature in harsh environments such as exposure to chloride and sulphate environments (Bassuoni & Nehdi, 2007). (Shi, et al., 2011), (Safehian & Ramezanianpour, 2013). Because synthetic fibres are more lightweight and convenient to install than concrete jacketing, they make it quick, easy, and affordable to retrofit structures (Mohammed, et al., 2019), (Hollaway & Teng, 2008). Thus, it has been demonstrated that the use of fibre-reinforced polymer (FRP) composites is a more practical alternative to traditional materials used in construction like concrete and steel for new construction as well as for retrofitting existing concrete structures.

However, synthetic fibres are made from petroleum-based polymers such as polypropylene and polyethene, making them non-sustainable materials, with significant consumption of energy and a bigger carbon footprint. A recent study by Ramachandran et al, 2013 showed that the production of the same amount of carbon fibre polymer (CFRP) composites as compared to natural fibre composites like flax fibre polymer composites resulted in 5 times more energy usage and 4.5 times the global warming potential. Another unfavourable aspect of synthetic fibres is that they require high cost for production, thus limiting their widespread application. Furthermore, synthetic fibres cannot be repaired or recycled, causing further environmental issues when discarded (Ramachandran, et al., 2023). Because of these drawbacks of synthetic fibres, the demand for substitute fibre materials has emerged.

2.2 Natural Fibres as a Potential Alternative to Synthetic Fibres

Natural fibres are becoming more popular recently because of their several environmental and economic benefits. As a result, the exploration of natural fibres as a potential replacement for synthetic fibres has become more popular. Natural fibres are inexpensive, renewable, biodegradable, and environmentally friendly (Joshi, et al., 2003); (Yan, et al., 2013). Natural fibres consume less energy even during production and processing (Wu, et al., 2017). Natural fibres have the ability to store carbon because they are produced from plants (Werf & Turunen, 2008); (Khalid, et al., 2021). Additionally, natural fibres are easier to dispose of after use are they are made from plants and are biodegradable (Navaratnam, et al., 2023). Because of all these factors, natural fibres have less impact on the environment than synthetic fibres.

Natural fibres have also shown to exhibit high tensile strength which can be compared to that of some synthetic fibres like glass fibres. For instance, hemp fibres have a high tensile strength of 550 to 900 Mega Pascals (MPa) (Sen & Reddy, 2011). Flax fibres, which are considered to be the strongest among natural fibres have demonstrated a tensile strength of 340 to 1600 MPa and Young’s modulus of 25 to 81 GPa (Kamarudin, et al., 2022). It has been demonstrated that using flax fibres as confinement in concrete can increase the composite structure's ductility while providing high ultimate compressive strength which is comparable to that of glass fibre reinforced polymer (GFRP) confinement (Yan & Chouw, 2013), (Xian, et al., 2014). In addition, Natural fibres are light-weight than synthetic fibres, which will help in lowering the overall weight of the building or other structures (Madueke, et al., 2021); (Rahman, 2021). Because of all the environmental and economic benefits, natural fibres appear to be a potential replacement for synthetic fibres.

Although natural fibres have numerous environmental advantages and have high tensile strength, they cannot be easily used as construction material in their natural state because of some limitations. Natural fibres like flax fibres show variable and inconsistent fibre quality which renders them unstable and unreliable material (Madueke, et al., 2021), (Benzarti, et al., 2018). Additionally, the bonding between hydrophilic fibres and hydrophobic polymers is not good enough as these materials do not adhere well to one another in the matrix (Kamarudin, et al., 2022).

High moisture absorption is another significant downside of natural fibres, which causes the natural fibres to swell and lose their mechanical strength. Natural fibres are sensitive to excessive moisture absorption and swelling because of their hollow, uneven structure and hydrophilic nature. (Benzarti, et al., 2018), (Stamboulis, et al., 2001), (Yan, et al., 2013). Alternate wetting and drying of natural fibre composites for a longer duration induces micro-cracking fibres and results in the degradation of mechanical strength (Stamboulis, et al., 2000). This moisture absorption and swelling of fibres also results in the weakening of the bonding between fibre and epoxy materials in the matrix resulting in compromised mechanical strength and modulus of natural fibre-reinforced polymer (NFRP) composites (Yan & Chouw, 2013). A study by Lu et al. (2022) also concluded that alternate drying and water absorption in flax fibres for a long duration leads to fibre-epoxy debonding in FRP composites (Lu, et al., 2022) which resulted in a significant decline in flexural strength in composite structure (more than 54% decline in flexural strength). Thus, before natural fibres may be used in place of synthetic fibres, these limitations must be addressed adequately.

There have been few studies that focused on the treatment of natural fibres using physical and chemical treatment methods. Some of the studies have successfully improved the moisture resistance in natural fibres considerably even if they could not completely eliminate the moisture absorption. Chemical treatments done with sodium hydroxide (NaOH), sodium bicarbonate (NaHCO3), and alkalization are successful in reducing the moisture absorption in natural fibres and thus increasing the performance of such fibres in wet conditions (Kamarudin, et al., 2022). Some of the treatments are found to increase the strength of natural fibres. In the recent study by Zhu, Zhu, Njuguna, & Abhyankar, 2013, alkali treatment done in flax fibres in a lab was found to increase the tensile strength of fibres by 21.9% by strengthening the bonding between fibre and epoxy material (Zhu, et al., 2013).

2.3 Use of Bio-Epoxy

Synthetic epoxies have significantly dominated the market due to their well-established production process and good performance as compared to bio-based alternatives. In recent years, Bio-based epoxies have gained some popularity due to increasing environmental concerns about synthetic epoxy and can offer similar or even better mechanical properties as compared to synthetic epoxies. Bio epoxy is emerging as a sustainable alternative, derived from renewable sources like plant oils and sugars. In this study, bio epoxy is used to produce composite material with flax fibres. Since flax fibres are being explored for their eco-friendly properties, it is more appropriate to pair them with natural epoxy to create a fully natural confining shell.

2.4 Related Studies

Few studies have tested the durability of flax fibres in the presence of moisture, and even fewer have examined the durability of flax fibre composites in salt water. Research on the compressive behaviour of concrete samples confined with flax fibre composites, particularly under the effects of salt water and high heat, is notably scarce. Further, none of the studies have considered the use of bio-based epoxies with flax fibres to form a fully natural composite material. Even if the studies directly related to this project cannot be found, some of the papers have examined the tensile strength of flax fibre composites under saltwater exposure. Most of these studies have reported that there is a considerable reduction in the strength of flax fibre composites when exposed to salt and moisture, however, the findings are not consistent with the amount of strength reduction. Some of the studies that have studied the effect of saltwater or moisture on flax fibre composites are discussed here.

In 2014, Mak, Fam, and MacDougall Studied the performance of unidirectional flax fibres when exposed to a 3.5% salt water solution for up to 365 days. The authors performed the tensile strength test on samples prepared by utilizing unidirectional flax fibre and epoxy resin. The tensile test on samples revealed a strength reduction of 31% over the period of 365 days when exposed to 3.5% salt solution at 55 degrees Celsius and a 27% reduction over the period of one year at a temperature of 40 degrees Celsius. They developed the relationship to estimate the strength reduction in flax fibre composites over time when exposed to saltwater and estimated that the flax fibre composite would retain 60% of its initial strength over 100 years when exposed to 3.5% salt solution at an annual mean temperature of 10 degree Celsius (Mak, et al., 2014).

Libo Yan and Nawawi Chouw (2015) studied the performance of flax fibre composites in a 5% alkaline solution as a confinement for concrete samples to study tensile and flexural strength. The exposure was conducted for 365 days. They found that tensile strength was reduced by up to 23.5% and flexural strength by up to 25.2% over the duration of exposure. (Yan & Chouw, 2015)

Cadu et al. (2019) conducted an experiment, where the flax fibre composites were exposed to alternate dampening and drying of samples over the duration of one year. The impact of moisture on flax fibre composites over the duration of one year was studied. They recorded a decrease of about 14% in ultimate tensile strength over the period of one year. (Cadu, et al., 2019).

Fiore et al. (2022) studied the flexural strength of flax fibres when exposed to saltwater as per the standard developed by the American Society for Testing and Material (ASTM); ASTM B117, for woven flax fibre fabric. The composite was exposed to saltwater for up to 30 days and then allowed to dry for 21 days. They observed both reversible and irreversible damage, with flexural strength dropping to 70% at the end of 28 days but some samples regaining to 97.5% after drying for 21 days. On average, a 10% reduction in strength for samples was observed when exposed to salt fog for 30 days.

Most of the studies focused on the tensile strength test of flax fibre composites alone. None of them were on the study of flax fibre composites when used as confinement material in concrete with axial compressive load. Also, the results of different studies are not consistent with each other.

2.5 Research Gaps

It can be concluded that, although some studies have been conducted on the performance of flax fibre composites in the presence of moisture, only a few studies have evaluated the performance of flax fibre composites in saltwater environments. Further, none of the studies are found to have considered the use of bio epoxy with flax fibres as confinement materials in construction. This indicates a noticeable gap in research when it comes to understanding the use of flax fibre and bio epoxy composite in saltwater environments and high ambient temperatures. Additionally, some of the experiments on the durability of flax fibre composites in saltwater have not shown consistent results, indicating the need for standardization of test procedures and the development of a reliable prediction model on the performance of flax fibre composites in saltwater environments.

This study addresses some of the research gaps as mentioned and focuses on the performance of flax fibre and bio epoxy composites when they are used as confinement material in concrete which are subjected to axial compressive load. One of the common ways of utilizing fibre-reinforced polymer composites in construction is by confining the concrete compressive members by fibre-reinforced polymer composites, where significant gain in performance can be achieved. Xian, et al. (2014) achieved almost double the compressive strength of a plain concrete sample with the application of only a few layers of flax fibres (Xian, et al., 2014).

Flax fibres were selected for this study as they are abundantly available and have higher tensile strength among the natural fibres (Kamarudin, et al., 2022). As the flax fibres are studied and used with environmental effects in mind, it is more complete if flax fibres are used together with natural epoxy to create a fully natural confining shell. The effect of salt water and high heat on flax fibre and bio epoxy composites on short-term durations of 3, 7, 15, and 28 days was evaluated and reported. This study was focused only on the failure mechanism under compressive load and the ultimate compressive strength test. In This study, the quantity of compressive strength loss in flax fibre polymer composites when exposed to saltwater and high ambient temperature, were evaluated.

2.6 Relevant Standards

The mix design utilized to prepare the concrete samples followed the standard- “Specification and supply of concrete, AS1379-2007”. (Standards Australia, 2007). The ratio of materials and the required consistency were determined according to this standard.

The Australian standard AS5100.8, “Bridge design, part 8: Rehabilitation and Strengthening of existing bridges”, provides a guideline on fibre-reinforced polymer (FRP) composite strengthening. The standard provides guidelines on how to apply fibre confinement, which will be used in the confinement of concrete samples in this experiment. It also outlines general assessment procedures, specifications for confinement materials, and the limitations of the confinement application. Additionally, the standard mentions equations to obtain minimum confinement pressure for effective utilization of fibre confinement. This equation is useful for calculating the number of confinement layers based on the tensile strength of fibre materials. (Standards Australia, 2017)

The exposure of the sample to salt water was conducted according to ASTM B117-11. The standard provides the requirements of apparatus, salt solution, procedure, and conditions required to create and maintain the salt spray (fog) test environment. The salt solution was prepared by mixing 5 parts by mass of sodium chloride in 95 parts of water. The temperature of the apparatus was set at 35 degrees Celsius as specified in the standard (ASTM International, 2011).

3. MATERIALS AND METHODOLOGY

This study involved conducting axial compressive tests on concrete cylindrical specimens confined with flax fibre and bio epoxy composite. The primary aim of the project was to investigate the performance of these composite materials when subjected to two different environmental conditions: 5% salt solution spray and a high temperature of 80 degrees Celsius, over varying durations. The project aimed to compare the ultimate strength of samples exposed to these conditions for different periods. The research was structured into five stages, which are outlined below.

3.1 Stage 1: Preparation of Concrete Specimens

Concrete cylindrical samples were prepared by mixing Ordinary Portland Cement (OPC), natural sand, coarse aggregates of 20 mm nominal size and natural water, all provided by the Flinders University laboratory. The mix design for normal strength concrete (NSC, 20 MPa) as specified in AS 1379 -2007 was used. The mixing of concrete was done using the mixer machine available at the Flinders University laboratory. A slump test was carried out first, before pouring the concrete into the mould to ensure the consistency of the concrete mix met the criteria of Australian Standard AS1379. The mixed concrete was then poured into the moulds and compacted using a vibrator table to expel any air voids to ensure a smooth surface was obtained. These two steps of manufacturing concrete cylinders are shown in Figure 1 below.

Figure 1: Slump test on concrete mix (Left) and concrete samples left for setting (Right).

The mixing of concrete was done in a single batch for all samples to ensure consistency among different samples. The samples were removed from the mould after 24 hours and submerged in water for 28 days for curing. The samples were cylindrical in shape and of size 100 mm in diameter and 200 mm in length. Two samples of bigger size with 150 mm diameter and 300 mm length were also moulded and utilized in testing the strength of the concrete. In total, 22 samples were prepared.

3.2 Stage 2: FRP Confinement

After the curing of concrete, the samples were dried to remove moisture from the surface and flax fibre and bio epoxy composite confinement was then applied to the samples. Firstly, a thin layer of bio epoxy resin was applied to the concrete surface, and the flax fibre sheet was wrapped around the concrete specimen in a hoop direction along with bio epoxy impregnation. A total of three layers of flax fibre sheets were wrapped around each sample with a 100 mm overlap at the end to ensure effective bonding. The composite was then cured as per the manufacturer's instructions and stored at room temperature for 7 days before being exposed to harsh conditions. The confinement application process followed the guidelines outlined in the Australian Standard AS 5100.8:2017. Figure 2 below shows the process of applying flax fibre and bio-epoxy composite confinement around the concrete sample.

Figure 2: Confining the concrete sample with composite (Left), Samples confined with composites (Middle), and confined samples after the curing process (Right).

Flax fibre used for this project was "200 g unidirectional flax fibre tape that was available at "Easy Composites" (https://www.easycomposites.co.uk/110g-unidirectional-flax-fibre). Unidirectional fibres were chosen for the project as they are more effective in applying confinement pressure on compression members as compared to woven fibres (Vincent & Ozbakkaloglu, 2013). Fibres were wrapped along the hoop direction as this is the most effective direction for fibre confinement as suggested by Vincent & Ozbakkaloglu, 2013. The tensile strength of the fibres as claimed by the manufacturer was 244(±13) MPa with Young's Modulus of 20 GPa. Other properties of Flax Fibre supplied by the manufacturer are provided in Table 1 below.

Table 1: Properties of flax fibres.

Fibre type	***The thickness of a single layer (mm)***	***Elastic Modulus (GPa)***	***Ultimate tensile strength (MPa)***	***Ultimate tensile strain %)***
Flaxtape 200	0.22 ± 0.02	20 ± 1	244 ± 19	1.5 ± 0.1%

The bio-resin "LB2 Epoxy Infusion Bio Resin", obtained from the same supplier as the flax fibre, was used for binding the flax fibre sheet to the concrete cylinder. As per the manufacturer's claim, the bio-resin was composed of 38% plant-derived content. The bio-resin was a two-component epoxy resin (Bio resin and hardener). The bio-resin was mixed and applied as per the manufacturer's recommendations.

The number of layers required for confinement was calculated using the equations from the Australian Standard AS5100.8 (2017). According to AS5100.8, the maximum confinement pressure of the fibre layer is given by the equation,

$$f_1 = \frac{2E_f * n * t_f * K_\varepsilon * \varepsilon_{fu}}{D} \qquad \text{Equation 1}$$

$$f_1 = \geq 0.08 * f'_c \qquad \text{Equation 2}$$

Where $f1$ = *maximum confinement pressure (MPa)*

Ef = *Modulus of elasticity of fibres (20000 MPa)*

n = *number of layers of wrapping*

t_f = *thickness of single layer (0.22 mm)*

K_ε = *Strain efficiency factor (0.55; AS 5100.8, A9.2.4)*

ε_{fu} = *Ultimate strain of flax fibres (1.5%)*

f'_c = *Compressive strength of concrete (24.46 MPa, obtained from testing)*

Substituting the values in Equation 1, the confinement pressures obtained are provided in Table 2.

Table 2: Confinement pressure calculations.

No of layers (n)	***Layers thickness, t_f (mm)***	***Total thickness (mm)***	***Confinement pressure, f_1 (MPa)***	***f_1/f_{co}***
1	0.22	0.22	0.726	0.0030
2	0.22	0.44	1.452	0.0594
3	0.22	0.66	2.178	0.0900

As observed from Table 2 above, Equation 2 is satisfied for three layers of flax fibre sheets of thickness 0.22 mm. Therefore, in this study, three layers of flax fibre sheet were used for confinement, as this is the minimum number of layers required for effective confinement. Additional layers were not used because previous studies indicated that they do not significantly enhance strength and may cause de-bonding issues. Additionally, some studies have shown that three layers of flax fibre provide optimal performance (Mak, et al., 2014).

3.3 Stage 3: Exposure to Salt Water and High Heat

After applying flax fibre confinement and curing of epoxy, the samples were exposed to harsh environmental conditions, which included saltwater and high heat. To expose the samples to saltwater, the corrosion chamber available in the Flinders University lab, "Ascott CC450" was utilized. The apparatus was set according to the ASTM B117-11 standard, exposing samples to 5% salt water solution at a temperature of 35 degrees Celsius. This test examines the suitability of flax fibre and bio-epoxy composite when used in marine structures, where the structures are continuously exposed to salt water. To expose the samples to high heat, the Geo-Con oven available at the Flinders University laboratory was utilized. The samples were placed in the oven which was set to the temperature of 80 degrees Celsius. This test examines whether the flax fibre and bio-epoxy composite can withstand high temperatures like those in deserts, where temperatures can exceed 55 degrees Celsius. Most of the related studies have considered 55 to 60 degrees Celsius for high ambient heat tests. However, some studies, including those by Kim et al. (2008) and Chu et al. (2004), have used a higher temperature of 80 degrees Celsius. Additionally, the review paper by Y.A. Al Salloum et al. (2013) indicated that the maximum temperature for high ambient temperature tests used by various researchers was 80 degrees Celsius. As a conservative approach, the maximum temperature used by these other studies was adopted in this study. The apparatus used for saltwater spray and high heat are shown in Figure 3 below.

Figure 3: Saltwater spray apparatus (left) and oven (right) utilized for the project.

The FRP-Wrapped samples were divided into 8 batches (Batch 4 to 11 in Table 3) where each batch was exposed to either saltwater spray or high heat for different duration of time. Samples were exposed for 3, 7, 14 and 28 days in both conditions.

3.4 Stage 4: Compression Test

For the compression test, an automatic testing machine (GEO-CON MCC8) was used, and the Multi Test Software Package provided with the testing machine was utilized for data collection. This Compression Testing Machine (CTM) was available at the Flinders University Laboratory. To measure strain in both the hoop direction and axial direction, 6 strain gauges were attached to the concrete specimen with 3 in the hoop direction and 3 in the axial direction of the cylinder. Additionally, Linear Variable Differential Transformers (LVDTs) were fixed to the setup to measure the displacement in the axial direction. Figure 4 below shows the attachment of strain gauges on the samples.

Figure 4: Strain Gauges attached to the samples (left); Sample ready for testing (Right).

After attaching strain gauges to the composite sample and fixing LVDTs to the setup, the sample was placed into the CTM. Figure 5 below shows the setup of the machine and devices for compression tests.

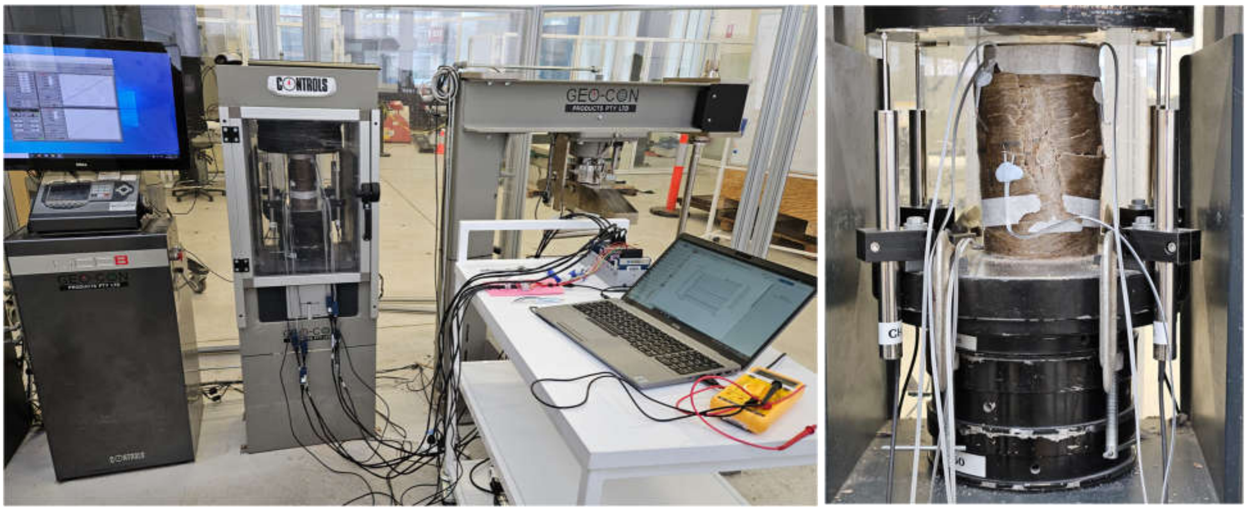

Figure 5: Experimental setup for testing (left); Setup showing LVDTs (right)

The setup and the connection of strain gauges were checked, and the axial compressive load was applied at a constant rate till the failure of the composite sample. The load was applied at the rate of 0.333 MPa/s, which is the minimum loading rate which is required by AS1012.9:2014 when conducting compression tests for concrete cylinders. The load and corresponding displacement with time were recorded by the CTM and LVDTs. The strain data was recorded through strain gauges with the help of Flex Logger software provided by the University. This data was then transferred to Microsoft Excel and stored for detailed analysis. The test was repeated for all the samples, and data were collected accordingly. Visual observations observed during the test were also recorded. The tests were carried out for the samples exposed to different scenarios as shown in Table 3 below.

Table 3: Test conditions and number of samples.

Batch no.	***No. of Samples***	***Test conditions***
1	2	7–day compression test
2	2	Plain concrete samples, 28 days
3	2	FRP-wrapped, control samples
4	2	FRP wrapped and exposed to salt water for 3 days
5	2	FRP wrapped and exposed to salt water for 7 days
6	2	FRP wrapped and exposed to salt water for 14 days
7	2	FRP wrapped and exposed to salt water for 28 days
8	2	FRP wrapped and exposed to high heat for 3 days
9	2	FRP wrapped and exposed to high heat for 7 days
10	2	FRP wrapped and exposed to high heat for 14 days
11	2	FRP wrapped and exposed to high heat for 28 days

Testing was conducted on a total of 22 samples with four samples designated for compressive strength testing and 18 samples wrapped with flax fibres and bio epoxy composites.

3.5 Stage 5: Data Analysis

During the compression test of composite samples, the following data were recorded by the machine and attached devices.

1 Load/Stress applied to the sample at different time steps (Recorded by machine).
2 Vertical and horizontal strain values captured at different time steps corresponding to the load applied. (Strain gauges).
3 Axial displacement of sample captured at different time steps corresponding to the load applied (LVDTs)

From the load, stress, displacement, and strain data obtained from the machine and the software, the ultimate strength and ultimate strain of each sample were calculated. The value of the load applied can

be converted to stress value by dividing the load by area and the strain values can be calculated by dividing the displacement values by the original lengths of samples. The ultimate strength, which is the maximum load that the sample can withstand, was calculated for each sample. Subsequently, the ultimate strength of all samples was compared to analyse their relative performance.
The increase in strength of the concrete sample after FRP application was assessed and compared to the estimated value calculated using the Australian Standard "AS 5100.8, 2017". Additionally, the strength of samples exposed to saltwater spray and high heat for varying durations was compared with each other and with control samples. The amount of strength reduction for each exposed sample was calculated. The findings of the study were also compared with the results of similar studies. Similar calculations and comparisons were also conducted for the ultimate strain values of each sample.

In addition to ultimate strength and strain, the stress-strain behaviour of each sample was studied by plotting stress vs strain curves. Firstly, the raw strain data obtained from the test was corrected and filtered with the stress data serving as a reference point for the actual test time. The stress versus strain curves were then plotted for composite samples. The stress vs strain curves for the samples exposed to different environmental conditions were compared with each other and with the control samples, and the observations were reported. As plain concrete is brittle, it exhibits sudden failure. On the other hand, as flax fibres exhibit ductile behaviour, FRP composite-wrapped concrete is expected to show a high strain value before failure.

4. RESULTS AND DISCUSSIONS

4.1 Visual Observations

The appearance of different composite samples is shown in Figure 6 below.

Figure 6: Control samples (left), samples exposed to high heat (middle) and salt spray (right).

It was observed that when composite samples were exposed to salt solution spray, they showed discolouration, indicating a reaction with a saline environment. As flax fibres are known to absorb moisture, the salt water was absorbed by the outer layer of FFRP causing this reaction. In contrast, when exposed to high heat, the samples showed no changes compared to the control samples. However, no cracks or delamination were observed in samples exposed to either environment.

4.2 Failure Modes

Failure patterns observed for plain concrete samples and FRP-confined specimens that were not exposed to harsh environments are shown in Figure 7 below.

Figure 7: Failure pattern observed in plain concrete samples (left) and FRP-wrapped samples (right).

The normal concrete samples failed by developing cracks throughout the surface and finally breaking. In the case of FRP-wrapped samples, failure occurred by developing vertical splitting of the composite wrapping and crushing of the concrete. This failure was instantaneous, with a loud bang from the breaking of the fibre composite. Such a failure mode is typical for all types of FRP-confined concrete samples under axial compressive load. This indicates that the samples did not experience premature failure due to debonding or shear failure, demonstrating that the confinement application was effective.

4.3 Ultimate Strength and Strain Data

4.3.1 Strength Gain from FRP-Wrapping

Table 4 and Figure 8 below show the strength data and comparison of the strength of plain concrete samples and FRP-wrapped control samples that were not exposed to either saltwater or high heat.

Table 4: Strength of plain concrete and FRP-wrapped samples.

Samples	***Plain Concrete samples***	***FRP Wrapped Control Samples***
Sample 1	24.21	45.89
Sample 2	24.71	44.61
Average	24.46	45.25

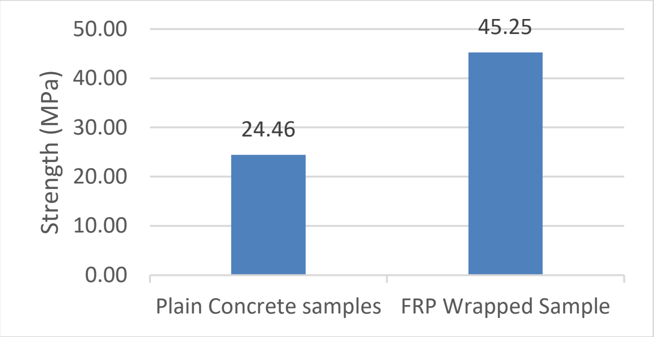

Figure 8: Strength of plain concrete sample vs FRP-wrapped sample.

As observed from the table and chart above, the confinement of concrete samples with flax fibre composite resulted in a significant gain in ultimate compressive strength. With three layers of flax fibre and bio epoxy composite wrapping, an additional 20.79 MPa of strength was gained, which is 1.85 times higher than that of plain concrete samples, representing an 85% increase in strength of plain concrete samples. This implies that flax fibre composite performs exceptionally well in construction applications, offering a substantial enhancement in the load-bearing capacity of concrete members.

The Australian Standard- AS 5100.8 provides the equation to predict the strength of the composite sample. The equation was used to estimate the strength of the composite sample knowing the strength of the plain concrete sample and flax fibre parameters. The ultimate compressive strength can be obtained using the equation.

$$f'_{cc} = f'_{c} + \varphi_f 3.3 k_a f_1 \qquad \text{Equation 5}$$

Where, f'_{cc} = *Maximum confined concrete compressive strength*

f_l = *2.178 MPa, as calculated in section 3.2 of this report*

f'_c = *compressive strength of concrete (=24.46 MPa, as tested)*

K_a = *cross-section efficiency (=1 for circular cross-section)*

Substituting these values in the equation, the ultimate strength for the confined sample obtained was:

$$f'_{cc} = 31.65 \text{ MPa.}$$

The average value of compressive strength of confined samples obtained from the experiment was 45.25 MPa, which is significantly higher than the estimated sample. This difference might be attributed to a conservative approach in determining the equations and related factors. Also, the flax fibre properties provided by the manufacturer might not be accurate. This comparison also confirms that the manufacturing method in the labs was of high quality and no premature failure occurred.

4.3.2 Exposure to Salt Solution Spray

The ultimate strength of composite samples exposed to saltwater spray for different durations and the comparison with control samples is shown in Table 5 below.

Table 5: Ultimate strength of composite samples exposed to salt spray.

Samples	**Control sample**	**3 Days**	**7 Days**	**14 Days**	**28 Days**
Sample 1	45.89	44.02	45.80	44.35	45.47
Sample 2	44.61	45.65	45.14	45.02	41.57
Average	45.25	44.84	45.47	44.69	43.52
Strength retention	100.0%	99.1%	100.5%	98.8%	96.2%

There was a slight fluctuation in ultimate strength with the duration of exposure, but the overall trend shows a slight decrease in strength over the 28-day period. This trend is visualized in the graphs given in Figure 9 and Figure 10 below.

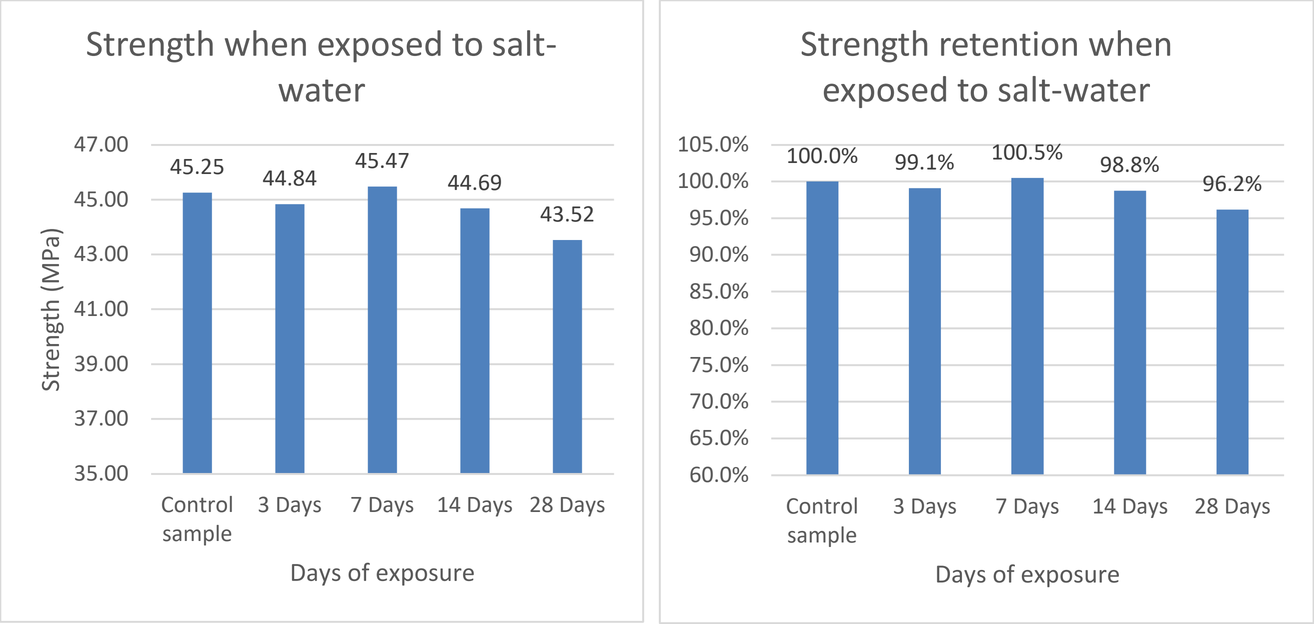

Figure 9: Chart showing compressive strength (Left) and strength retention (Right) of samples exposed to salt water.

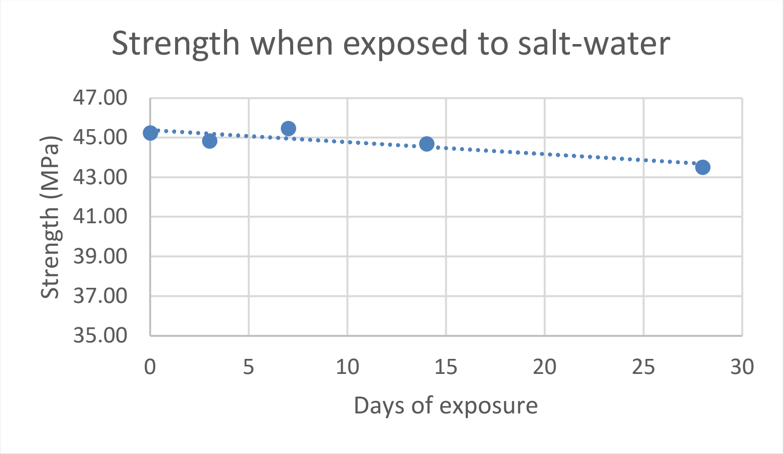

Figure 10: Chart showing the gradual decline of compressive strength, when exposed to salt water.

Overall, the flax fibre composites showed relatively good retention of their ultimate compressive strength even after exposure to salt spray for up to 28 days. Over the duration of 28 days, there was a decrease in strength by 3.8%, resulting in a strength retention of 96.2%. This indicates that while there is a slight reduction in strength over time, the composites maintain most of their structural integrity. Also, the flax fibre and bio-epoxy combination was a successful combination indicating bio-epoxy can be a viable alternative to synthetic epoxy.

The ultimate axial strain of the samples when exposed to salt water is shown in Table 6 and illustrated in Figure 11 below. The strain values were calculated from the displacement values recorded using LVDTs.

Table 6: Ultimate strain of samples exposed to salt water.

Samples	***Control sample***	***3 Days***	***7 Days***	***14 Days***	***28 Days***
Sample 1	0.01745	0.01760	0.01677	0.01487	0.01589
Sample 2	0.01520	0.01586	0.01717	0.01506	0.01275
Average	0.01632	0.01673	0.01697	0.01496	0.01432

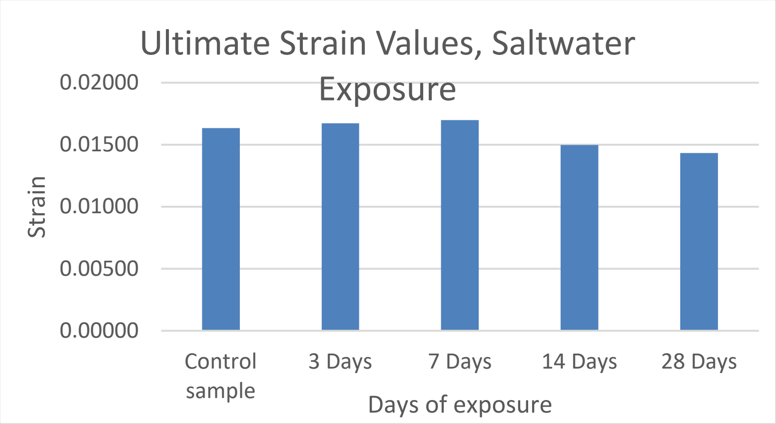

Figure 11: Chart Showing the ultimate Strain of samples exposed to salt water.

Similar to the strength values, there was also some fluctuation in ultimate Strain values with the duration of exposure. The ultimate strain also decreased over the period of 28 days, indicating a gradual deterioration in the material's ability to withstand deformation under stress.

When comparing the strength reduction with other similar studies, those studies indicated a strength reduction of up to 10% for the exposure of 28 days in similar lab settings while other studies indicated a strength reduction of 30 to 50% reduction in strength reduction when exposed for 365 days

4.3.3 Exposure to High Heat

The ultimate strength of composite samples, when exposed to the high heat of 80 degrees Celsius for different durations and the comparison with control samples is shown in Table 7 below.

Table 7: Ultimate stress of composite samples exposed to high heat.

Samples	***Control sample***	***3 Days***	***7 Days***	***14 Days***	***28 Days***
Sample 1	45.89	42.63	41.46	50.19	45.15
Sample 2	44.61	47.03	44.50	47.10	48.00
Average	45.25	44.83	42.98	48.65	46.58
Strength retention	100.0%	99.1%	95.0%	107.5%	102.9%

The data shows an overall increase in compressive strength of composite samples with the duration of exposure, despite large fluctuations in strength observed for the 7-day and 14-day exposures. The visualization of this data is provided in Figure 12 and Figure 13 below.

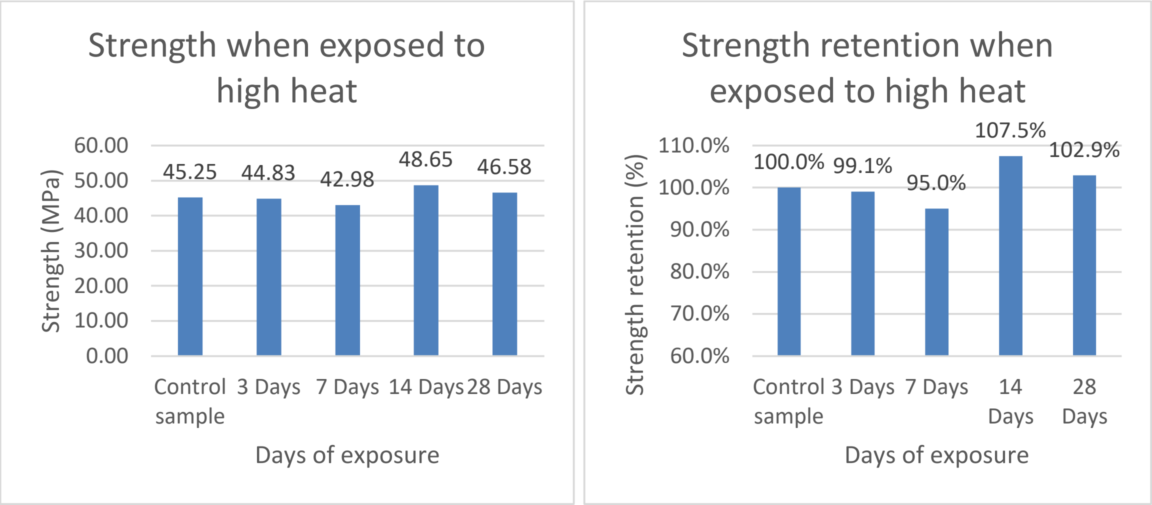

Figure 12: Ultimate strength (Left) and strength retention (right) for the samples exposed to high heat.

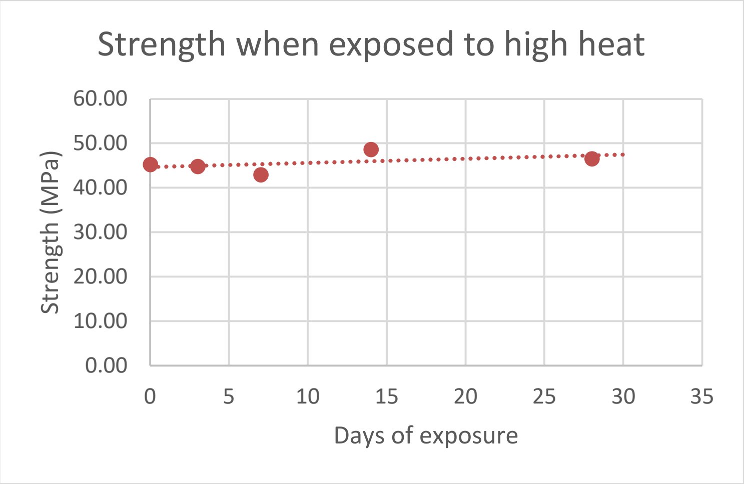

Figure 13: Chart showing the gradual increase in compressive strength, when exposed to high heat.

Despite fluctuations in the ultimate strength for samples exposed to high heat for different durations, the overall trend indicates a slight gain in strength with increased exposure duration. This suggests that the material might undergo beneficial changes at high temperatures, which could be advantageous in certain construction scenarios where heat resistance is required. This behaviour of flax fibre and bio epoxy composite is possibly due to the curing effect of heat on epoxy resin, thereby improving the material's mechanical properties and overall structural integrity.

The ultimate axial strain of the samples when exposed to high heat is shown in Table 8 and illustrated in Figure 14 below. The strain values were calculated from the LVDT recorded displacement values.

Table 8: Ultimate strain of the samples exposed to high heat.

Samples	***Control sample***	***3 Days***	***7 Days***	***14 Days***	***28 Days***
Sample 1	0.01745	0.01623	0.01584	0.02029	0.01681
Sample 2	0.01520	0.02138	0.01984	0.02079	0.01746
Average	0.01632	0.01881	0.01784	0.02054	0.01714

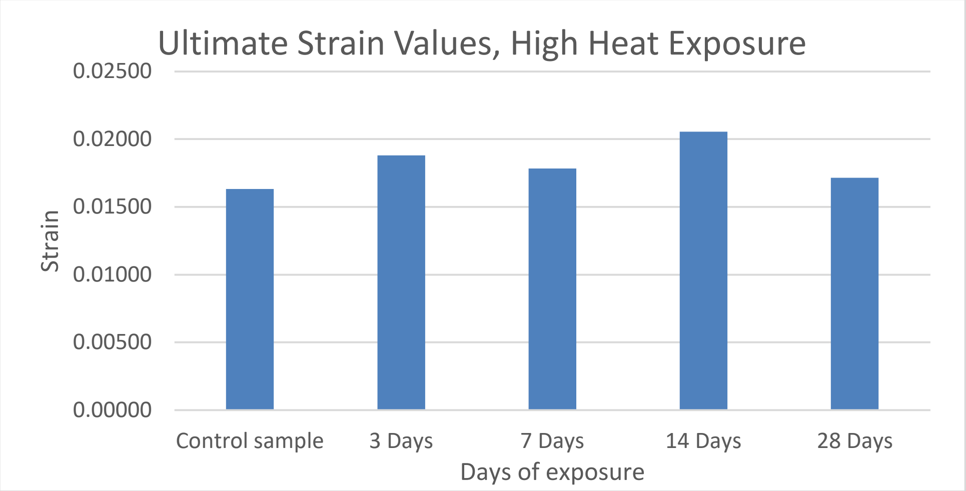

Figure 14: Chart showing the ultimate strain of the samples exposed to high heat.

As observed in the table and chart above, ultimate strain values follow the trend of ultimate strength showing some fluctuations with an overall increase in ultimate strain for samples exposed to high heat for 28 days. This indicates an improvement in the material's ability to withstand deformations under stress when exposed to high heat of up to 80 degrees Celsius. This phenomenon can be attributed to the beneficial effects of high heat on epoxy curing. The improved strength of the epoxy likely contributes to enhancing the overall strength and ultimate strain capacity of the FRP confining shell.

4.4 Stress-Strain Curves

The stress-strain curve for the control samples wrapped with flax fibre composites obtained from the experiment is given in Figure 15 below.

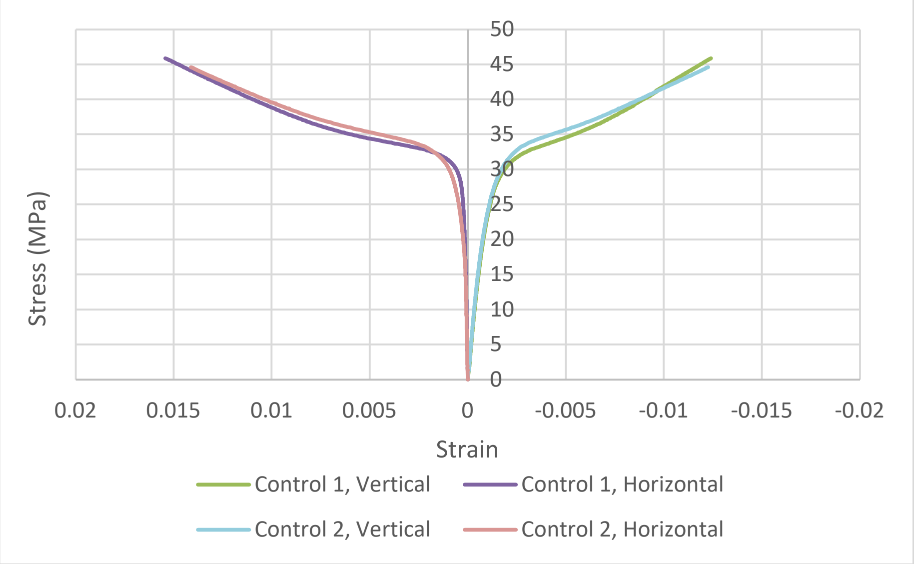

Figure 15: Stress vs strain curve for control samples.

The stress-strain curves were plotted from the strain data obtained from strain gauges. The graph shows the stress-strain relationship for both hoop direction and axial direction. The curves obtained from the experimental data for control samples align with the expected shape of the curve in Figure 17. This indicates that the confinement of concrete using flax fibre and bio-epoxy resin is effective.

4.4.1 Exposure to Salt Solution Spray

Figure 16 shows the stress vs strain curves for samples exposed to salt water for various durations.

Figure 16: Comparison of stress-strain curves for samples exposed to saltwater spray.

As seen in the graph, the samples exposed to saltwater for different durations showed similar stress-strain behaviour regardless of exposure duration. Although there was a slight decrease in ultimate strength and ultimate strain over the duration of 28 days, no specific changes in trend were observed in stress-strain behaviour. The individual stress-strain curves for each sample are provided in Appendix A2 of this report.

4.4.2 Exposure to High Heat

Figure 17 shows the stress vs strain curves for samples exposed to salt water for various durations.

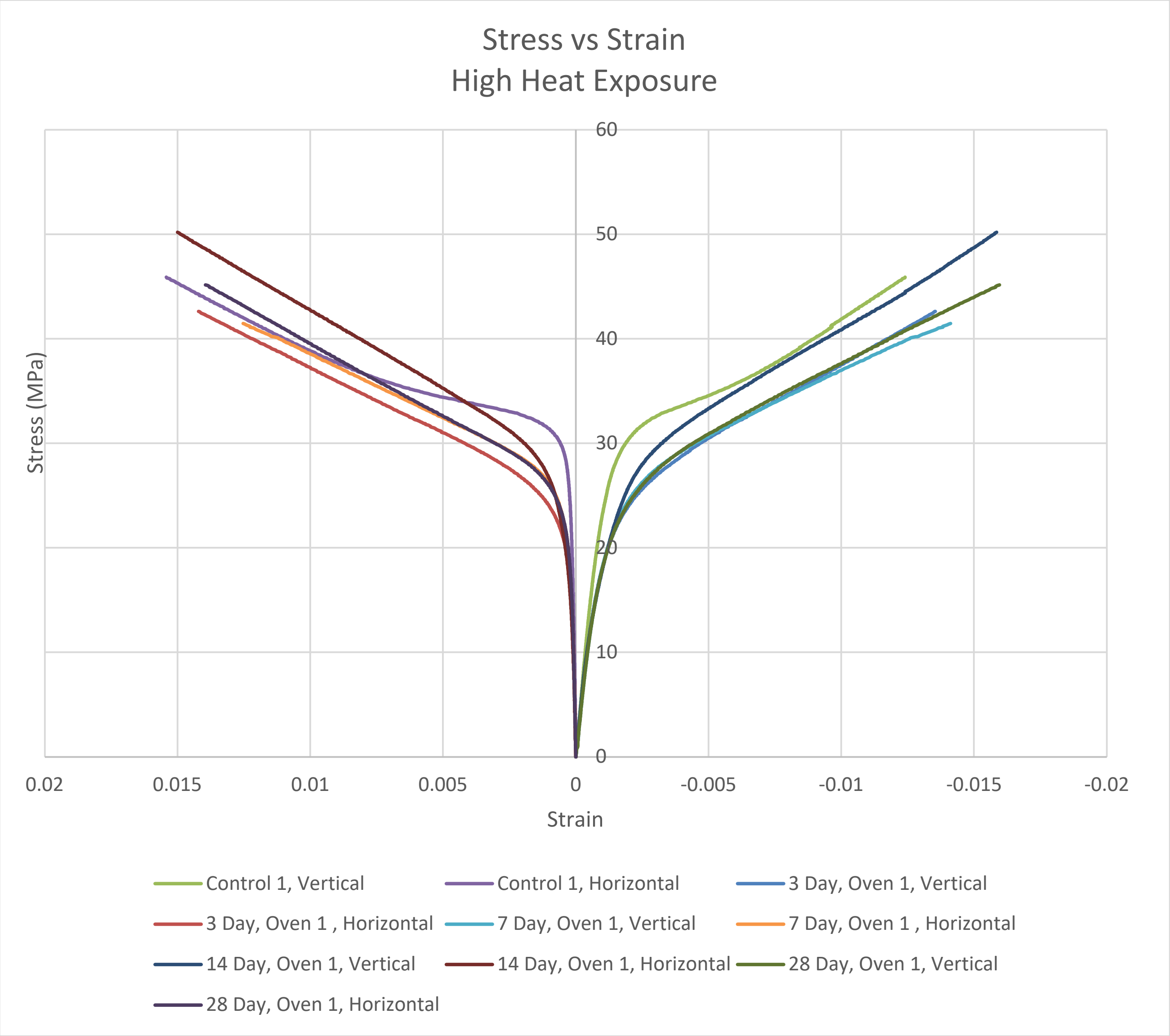

Figure 17: Comparison of stress-strain curves for samples exposed to high heat.

The samples exposed to high heat for different durations showed similar stress-strain behaviour regardless of exposure duration. However, the stress-strain curves for both axial and horizontal directions are scattered more as compared to that of samples exposed to salt water, with no specific changes or trends observed in stress-strain behaviour. The individual stress-strain curve for each sample is provided in Appendix A2 of this report.

5. CONCLUSIONS

This experimental study focused on examining the impact of saltwater spray and high heat on flax-fibre and bio-epoxy composites when they were used as confinement material in concrete compressive members. A total of 22 concrete samples were prepared, with FFRP confinement applied to 18 of them. The amount of strength gained from Flax fibre composite confinement was assessed. Further, flax fibre composite samples were exposed to either a 5% saltwater solution or to high heat of 80 degrees Celsius for the periods of 3, 7, 14 and 28 days. The effects of such conditions on flax fibre and bio epoxy composite were studied by testing the compressive strength of samples. Comparisons of strength, ultimate strain, and stress-strain behaviour were made among the samples exposed to these conditions for different durations of time and with the control samples.

The study revealed that applying flax fibre and bio-epoxy composite confinement can achieve significantly higher compressive strength in concrete samples. In this test, an increase in axial compressive strength of 85% was achieved with three layers of flax fibre confinement. When exposed to saltwater, the flax fibre composite samples showed a slight decrease in ultimate compressive strength and ultimate axial strain, with a 3.8% decrease in compressive strength over the exposed period of 28 days. Conversely, exposure to high heat resulted in a slight increase in both strength and ultimate strain over 28 days, with an increase in compressive strength by 2.9% for 28-day exposure, likely due to the curing effect of heat on epoxy. The stress-strain curves for composite samples behaved as expected, but no particular trend was observed for samples exposed to either saltwater spray or high heat.

It was concluded that flax fibre and bio epoxy were a successful combination and resulted in a strength increase of 85 % compared to plain concrete cylinders. A minimal decrease in strength when exposed to saltwater shows that flax fibre and bio-epoxy composites have strong potential for long-term durability and effectiveness in construction applications, offering an eco-friendly alternative to traditional synthetic materials. This also suggests that bio-epoxy can be a viable replacement for synthetic epoxy when used with natural fibres like flax fibres. A slight gain in compressive strength when exposed to high heat indicates that the materials could have beneficial effects in certain applications when heat resistance is required. In this study, samples were exposed to harsh conditions only for a duration of 28 days only due to time and resource limitations. However, in real life, structures are exposed to such environments for several decades. Therefore, to fully understand the performance of flax fibre and bio epoxy composite in construction applications, a long-term exposure, preferably a minimum of one year is recommended to observe the actual performance of flax fibre composites in saltwater or high-heat environments.

6. RECOMMENDATIONS FOR FUTURE WORK

Based on the observations during the experimental study, the following recommendations are made:

1. **Long-term Study on Saltwater Exposure:** The effect of saltwater on the flax fibre and bio-epoxy combination can be investigated over a minimum period of one year to better understand long-term impacts.
2. **Resource-efficient Testing Method:** A saltwater bath can be used for long-term exposure tests instead of a saltwater spray apparatus, as it requires fewer resources.
3. **Comparison with Synthetic Epoxy:** Tests can be conducted on flax fibre composite samples using both bio-epoxy and synthetic epoxy for a more comprehensive comparison.

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