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SHORT-TERM DURABILITY OF HEMP FIBERS

by
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Despite the recent research on the durability of natural fibers, the durability performance of natural-fiber strengthened structures is not yet widely investigated. In this research, short-term durability tests on hemp-fiber confined concrete cylinders made up of one layer of hemp-fiber bundles were conducted to study their behavior. Compressive testing was performed after wetting and drying cycles in both water and seawater. Moreover, tensile testing on hemp-fiber bundles was conducted to study the effect of extended W/D cycles and prolonged exposure to moisture (1,800 hours).

Hemp-fiber confined concrete cylinders showed promising results where there was no significant change in both compressive strength and ductility in comparison to control wrapped cylinders. Regarding tensile testing, after prolonged exposure to water, hemp-fiber bundles were completely destroyed. On the other hand, epoxy coating offered a suitable protected configuration to hemp-fiber bundles. Resistance to seawater was highly apparent in the conservation of tensile stresses. Therefore, natural fibers could be used as alternative to synthetic fibers when taking their drawbacks into account.

Keywords: Hemp-fiber bundles; Durability; Tensile testing; Compression test.

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CHAPTER I

INTRODUCTION

A. General

Green composites are recently gaining more attention along with raised world's concern toward the concept of sustainability. Jute, coir, flax, bamboo, and hemp are examples of sustainable materials that are being widely explored by many researchers to substitute synthetic materials. Natural fibers have several promising advantages such as low specific weight, low cost, and the fact that they are biodegradable, non-abrasive and renewable eco-friendly resources. In addition, their specific mechanical properties are comparable to those of synthetic fibers [1]. Civil engineering is one of the most significant areas for future use of natural fibers as construction and building materials [2]. The first use of natural fibers as a strengthening material was in ancient Egypt some 3,000 years ago where clay was reinforced by straw to form bricks [3]. Today, this new technology of natural fiber polymers is being explored widely. Various research papers and experiments have proved the effectiveness of using natural fibers in concrete mix design or as a strengthening material against earthquake through concrete confinement. The new technology of cellulose FRP composites offered encouraging results in terms of strength, stiffness, ductility, and energy absorption. Flax fabric reinforced polymer composites used as external wrappings by Yan [4] have resulted in an increase in the ultimate compressive strength, axial strain, fracture energy, and ductility of plain concrete cylinders. In flexure, this FRP strengthening increased lateral load, deflection, flexural strength and fracture energy of the concrete beams.

The properties of natural fibers depend highly on their chemical composition. Cellulose fibers are mainly made up of cellulose, hemicellulose, lignin, pectin, and wax in different quantities. The cellulose component provides natural fibers with strength, stiffness, and stability [5]. Hemicellulose is responsible for the biodegradation, moisture absorption, and thermal degradation of the fiber, whereas lignin is responsible for the UV degradation [6]. However, the main drawback of these materials is their high variability which leads in return to variability in their physical and mechanical properties. Moisture absorption is another significant disadvantage affecting the mechanical properties of natural fibers. Moisture absorption can lead to dimensional variation in the composites, fiber swelling and eventually rotting due to fungi attack. A suitable surface treatment may be a possible solution to overcome the drawbacks of moisture absorption [7]. Moreover, the presence of hydroxyl and other polar groups in natural fibers results in incompatibility between fibers and polymer matrices which leads to a lower interface strength when compared to glass and carbon composites [8].

Thus, durability and expected lifetime are main short-comings of natural fibers when used in structural applications. In fact, green composites, similar to synthetic composites but to a different extent, are prone to degradation and deterioration with time. Comparisons with synthetic fiber reinforced polymers reveal that both synthetic and natural fiber reinforced polymers suffer from severe degradation in mechanical properties after moisture immersion [2]. Hristozov et al. [9] indicated that flax specimens show slightly higher strength retention than glass specimens after moisture attack, and the long-term mechanical behavior of flax composites is not worse than glass composites. Therefore, prior to implementing natural fibers reinforced polymer composites in the construction market, it is compulsory to investigate their durability and performance upon exposure to different environmental conditions.

B. Definition

Durability of fiber reinforced polymers as defined by Karbhari et al. (2003) (as cited by Sen and Paul [10]) is “the ability of these materials to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental condition.” In fact, natural fibers are more susceptible to degradation and deterioration over time, so durability issues must be of a great concern when natural fibers are used in civil construction industry.

Several environmental factors affect the durability and performance of fiber reinforced polymer composites during their in-service life. These factors include: impact of high humidity and rain, impact of ultraviolet radiation, effect of freezing and thawing, high temperature and/or fire effect, saltwater influence, basic, acid and alkaline solution effect, or a combination of these multiple listed factors [2]. These factors may affect the mechanical and microstructural properties of natural fibers reinforced polymer composites, and may to some extent restrict their use under special circumstances.

C. Objective

The foremost objective of this research is to conduct a preliminary study of the durability of natural fibers when used in real-life construction applications, and to investigate their durability performance as well as their behavior in different environmental exposures. Lack of data is a major constraint that should be addressed before the widespread acceptance of natural fiber reinforced composites in engineering applications [2, 5, 11]. In this research, the properties of hemp-fiber confined concrete and hemp fibers will be explored when subjected to water and seawater. It is well known that natural fibers have the tendency to absorb water which leads to the deformation of their surface due to swelling which in return leads to an alteration of their mechanical and microstructural properties. Thus, further research and exploration are needed before the acceptance of these "sustainable materials" as an alternative to synthetic carbon or glass fibers.

D. Significance

There are two main significances of this research:

- Very little information exists about the behavior of hemp fibers in seawater.
- The durability of natural-fiber confined cylinders is not explored yet under the effect of moisture. Several tests tended to study their tensile strength, but no research investigated the effect of water/seawater on the confinement. Therefore, in this research a short adopted durability test will make it possible to study the behavior of natural fibers, "*hemp fiber*" in this study.

E. Outline

Chapter 2 examines the durability studies of natural fiber reinforced polymer composites, cellulose based natural fibers, and natural fiber reinforced cementitious composites, as well as it gives an overview of significant research concerning the durability of synthetic fibers. Chapter 3 discusses the used methodology, the instrumentation, and the testing procedure, as well as it lists the used materials. The analysis of the experimental results is discussed in Chapter 4. Chapter 5 includes a summary and a conclusion along with proposed future research.

CHAPTER II

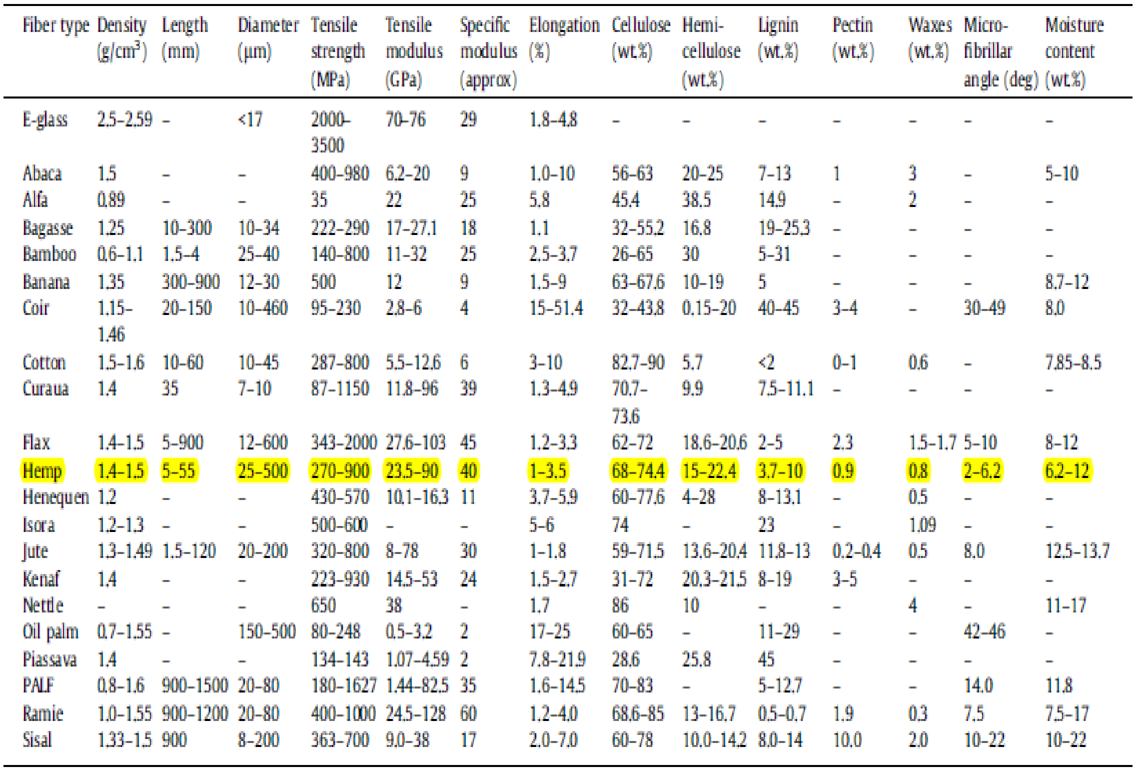
LITERATURE REVIEW

A. Introduction

Natural fibers are being used as alternatives to synthetic fibers such as carbon, glass, and aramid fibers. Among the most used natural fibers as a reinforcement is hemp fiber. Hemp fiber is a bast fiber extracted from the stem of the hemp plant [1]. China is among the world's leading producer of hemp with other major producers in France, Chile, and the Democratic People's Republic of Korea [12]. Nowadays, hemp fiber production is considered to be less than 0.5% of total world production of natural fibers [7]. In addition to the enormous environmental benefits hemp fiber offers, it has the potential of producing important quantities of paper, textiles, carpet, nets, food, medicine, paint, oil, and fuel [13].

The high tensile strength and stiffness of hemp fiber make it a promising material to replace synthetic fibers as a reinforcement. Typical physical and tensile properties of natural fibers are shown below in Table 1, as reported by Dittenber and GangaRao [14] in their critical review of recent publications on use of natural composites in infrastructure. In fact, the tensile strength and modulus of a single hemp fiber vary between 270-900 MPa and 23.5-90 GPa, respectively.

Table 1: Physical and tensile properties of natural fibers and glass fibers [14]



Fiber type	Density (g/cm^3)	Length (mm)	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Specific modulus (approx)	Elongation (%)	Cellulose (wt.%)	Hemi-cellulose (wt.%)	Lignin (wt.%)	Pectin (wt.%)	Waxes (wt.%)	Micro-fibrillar angle (deg)	Moisture content (wt.%)
E-glass	2.5–2.59	–	<17	2000-3500	70-76	29	1.8–4.8	–	–	–	–	–	–	–
Abaca	1.5	–	–	400–980	6.2–20	9	1.0–10	56–63	20–25	7–13	1	3	–	5–10
Alfa	0.89	–	–	35	22	25	5.8	45.4	38.5	14.9	–	2	–	–
Bagasse	1.25	10–300	10–34	222–290	17–27.1	18	1.1	32–55.2	16.8	19–25.3	–	–	–	–
Bamboo	0.6–1.1	1.5–4	25–40	140–800	11–32	25	2.5–3.7	26–65	30	5–31	–	–	–	–
Banana	1.35	300–900	12–30	500	12	9	1.5–9	63–67.6	10–19	5	–	–	–	8.7–12
Coir	1.15-1.46	20–150	10–460	95–230	2.8–6	4	15–51.4	32–43.8	0.15–20	40–45	3–4	–	30–49	8.0
Cotton	1.5–1.6	10–60	10–45	287–800	5.5–12.6	6	3–10	82.7–90	5.7	<2	0–1	0.6	–	7.85–8.5
Curaua	1.4	35	7–10	87–1150	11.8–96	39	1.3–4.9	70.7-73.6	9.9	7.5–11.1	–	–	–	–
Flax	1.4–1.5	5–900	12–600	343–2000	27.6–103	45	1.2–3.3	62–72	18.6–20.6	2–5	2.3	1.5–1.7	5–10	8–12
Hemp	1.4–1.5	5–55	25–500	270–900	23.5–90	40	1–3.5	68–74.4	15–22.4	3.7–10	0.9	0.8	2–6.2	6.2–12
Henequen	1.2	–	–	430–570	10.1–16.3	11	3.7–5.9	60–77.6	4–28	8–13.1	–	0.5	–	–
Isora	1.2–1.3	–	–	500–600	–	–	5–6	74	–	23	–	1.09	–	–
Jute	1.3–1.49	1.5–120	20–200	320–800	8–78	30	1–1.8	59–71.5	13.6–20.4	11.8–13	0.2–0.4	0.5	8.0	12.5–13.7
Kenaf	1.4	–	–	223–930	14.5–53	24	1.5–2.7	31–72	20.3–21.5	8–19	3–5	–	–	–
Nettle	–	–	–	650	38	–	1.7	86	10	–	–	4	–	11–17
Oil palm	0.7–1.55	–	150–500	80–248	0.5–3.2	2	17–25	60–65	–	11–29	–	–	42–46	–
Piassava	1.4	–	–	134–143	1.07–4.59	2	7.8–21.9	28.6	25.8	45	–	–	–	–
PALF	0.8–1.6	900–1500	20–80	180–1627	1.44–82.5	35	1.6–14.5	70–83	–	5–12.7	–	–	14.0	11.8
Ramie	1.0–1.55	900–1200	20–80	400–1000	24.5–128	60	1.2–4.0	68.6–85	13–16.7	0.5–0.7	1.9	0.3	7.5	7.5–17
Sisal	1.33–1.5	900	8–200	363–700	9.0–38	17	2.0–7.0	60–78	10.0–14.2	8.0–14	10.0	2.0	10–22	10–22

Hemp fibers are hydrophilic and absorb moisture where the moisture content of hemp fibers varies between 5 and 10% and may exceed this value [7]. Actually, “hydrogen bonds are formed between the hydroxyl groups (__CH_2OH) of the cellulose molecules and water” as soon as hemp fibers are in a moisture condition [15]. The composites reinforced with 56% of hemp fiber by weight lost 35% of its tensile strength and 60% of its modulus after 3,700 hours of immersion in water due to plasticization of polyester matrix and hemp fiber and loss in stiffness of hemp fibers [15]. Similarly, after only 1 day of water immersion of ramie fiber reinforced phenolic composites, the flexural strength and modulus were dramatically reduced. This was mainly attributed to hydrolysis of the resin matrix and ramie fiber, as well as degradation of fiber bonding. In fact, drying was proved to “remove the plasticization effect of the absorbed water,” but it cannot recover permanent damages [16].

Moisture absorption of hemp fibers along with its high variability will remain a challenge for researchers to explore and so overcome. Nevertheless, the advantages of its promising mechanical properties make it a viable competitor in the civil construction industry in the near future.

B. Durability studies on natural fibers

If being used in construction civil engineering industry, natural fibers used in cement or as strengthening material will be exposed to different environmental conditions which might affect their performance and quality, and thus raise durability concerns. In order to have durable cellulose fibers, fiber treatment and matrix treatment are used as promising strategies. Chemical fiber treatment (e.g. alkali treatment and silane treatment) and physical treatment (e.g. plasma and corona treatment) aim to achieve better mechanical and thermal properties of natural fiber reinforced composites. Matrix treatment which includes the use of low alkaline concrete or the addition of pozzolans to portland cement aims to increase the durability of fiber reinforced cementitious composites [1]. In the following subsections, studies on the durability of natural fiber reinforced polymer composites, cellulose based natural fibers, and natural fiber reinforced cementitious composites will be presented.

1. Durability of natural fiber reinforced polymer composites

To date, few studies have examined the durability of natural fibers reinforced polymer composites. Yan et al. [11] investigated the durability of bidirectional woven flax fibers using the typical hand lay-up process. Specimens were exposed to accelerated weathering process composed of repetitive cycles of: (1) 12 hours of UV light exposure at 60º C, (2) placing at room temperature for 3 hours, (3) spraying water to the exposed surface and exposed to UV light for 6 hours at 60ºC, and (4) placing again at room temperature for 3 hours before the next cycle. After 1,500 hours exposure, the mechanical properties of the specimens were studied. The tensile strength, modulus and strain at break of the weathered flax-epoxy composites decreased 29.9%, 34.9%, and 31.1%, respectively. Similarly, the flexural strength, modulus, and strain of the weathered specimens had been evaluated. 10%, 10.2%, and 13.7% loss of the previous mechanical properties were respectively reported. Upon investigating the surface morphology of weathered fiber composites, the general failure mechanism of the composites under tension was observed to be fracture of fiber, deboning and fiber pull-out, and matrix cracking. Thus, the weathered composites showed more fiber pull-out and matrix cracking failure modes when compared to the controlled specimens. In another research study by Yan et al. [17], the fire performance of the flax fiber reinforced polymers was evaluated. Light Oxygen Index (LOI) is a tool used to predict the fire performance of any material. Higher LOI value indicates a better performance when exposed to fire. Flax and hemp fabric/epoxy composites exhibited LOI of 23.6 and 22, respectively. Natural fibers reinforced polymers showed a better fire performance, and are thus harder to ignite burning than glass fabric/epoxy composites which showed LOI value of 21 as reported by Marosi et al. (as cited by Yan et al. [17]).

Yan and Chouw [2] also studied the effect of water, seawater, and alkaline solution on the properties of flax fabric/epoxy composites that are aimed to be used as an external strengthening material. Hand lay-up process was used to fabricate flax fabric/epoxy composites. The specimens were immersed in water, seawater of 3.5% salinity, and 5% NaOH for 365 days at room temperature. Weight change, tensile test, flexural test, and surface morphology studies were performed to analyze the effect of these environmental conditions on the properties of flax fibers. According to Yan and Chouw [2], the surface changed from yellow color and semi-transparent to dark and dizzy in both water and seawater solution, and to a transparent surface in NaOH solution. This color change can be attributed to chemical changes occurring in the epoxy matrix. The weight change is another indicative property of the durability of the material. The flax-epoxy composites increased in weight in the first two months in the three solutions due to water absorption, and its weight stabilized afterwards to reach the saturation level. On the other hand, the reduction in tensile strength was significant in the three solution ageing; 22.6%, 28.3%, and 31.1% reduction in tensile strength in water, seawater, and sodium hydroxide solution were respectively reported. Similar results were observed for the tensile modulus with a reduction up to 36.4%. In fact, the degradation of flax fibers, epoxy matrix, and the bond at the interface was the main reason behind this significant decrease in tensile strength. Cracks and voids were generated in the epoxy due to the immersion process, thus allowing the moisture to penetrate into the flax fiber. This resulted in a weak bond due to the breakdown of cellulose and hemicellulose. Similarly, the flexure strength and modulus declined for all the three aged specimens, but in a lesser extent than that of the tensile strength and modulus. Analyzing the tensile and flexural stress-strain curves of the aged composites, the three different solutions did not exhibit any modification to the trends of these curves. A primary linear elastic stress-strain behavior, then an approximate linear pattern until failure was reported. The aged surface of flax/epoxy composites showed micro-cracks allowing infiltration of the solutions into the composites. Thus, fiber pull-out and fiber/matrix de-bonding were the failure mechanisms of the aged composites after continuous immersion. Comparing the results of this study with synthetic fiber-reinforced polymer composites' results, it was clear that both were severely degraded after immersion in water, seawater, and alkaline solutions.

Similarly, Michel and Billington [18] investigated the durability of poly-hydroxybutyrate biopolymer films and PHB-hemp fiber reinforced composites by performing accelerated weathering testing. The reduction in tensile strength and stiffness of partially bio-based composites altered between 25 to 47% and 15 to 62%, respectively. Michel and Billington [18] explicated this decrease due to the "combined cyclic fiber swelling and embrittlement of the bio-polymer matrix through photo-oxidation and hydrolysis." PHB-hemp composites experienced color change, lightening, cracking, mass loss, and increased cross sectional area as well as a faster rate of degradation with respect to synthetic polymer bio-based composites. Thus, bio-based composites may be useful for non-structural or temporary construction application. In a research conducted by Singh et al. [19], jute composites were subjected to different environmental exposures to study their mechanical and physical properties. Jute composites were studied under various humidity, hydrothermal, and weathering conditions. Three different methods were followed to investigate the hydrothermal effect on jute composites: cyclic, durability cycles, and accelerated water aging. Under hydrothermal ageing, a significant drop in tensile strength was observed due to moisture variation which caused the jute composites to swell then dry repeatedly. In fact, the mechanical properties of aged jute composites decreased significantly with respect to fresh jute composites, and the surface was deteriorated considerably under high humid/wet environment. In another research paper by Sen and Paul [10], the durability of both natural and synthetic fiber reinforced polymers was examined. Both natural and synthetic fibers showed similar performance when left in water at 100°C for 30 minutes. Sen and Paul [10] also investigated the effect of thermal ageing on the properties of fibers by exposing them to two different environments: (1) 10 hours at 75°C, and (2) 6 hours at -75°C. Both fibers showed increase in tensile strength under high temperature, and a decline under freezing condition due to formation of matrix-cracks and low adhesion of fiber/matrix. Regarding the fire flow test, natural fiber composites showed better fire performance when compared to artificial ones. Thus, natural fiber polymers (sisal/jute woven FRP) displayed promising results in this research study.

Dhakal et al. [20] studied the mechanical properties of hemp fiber reinforced unsaturated polyester composites upon immersion in water at 25°C and 100°C for different time durations up to 888 hours. When hemp fibers were immersed in water, fibers swelled and then micro-cracking occurred leading to the transport of water through the matrix. The weight gain was higher for samples at high temperature than that of room temperature. The tensile strength of the samples at room temperature for unsaturated polyester and 2 hemp fiber layers reinforced samples increased due to crosslinking enhancing the tensile strength, while for higher fiber contents of 3 and 4 layers, the tensile strength of immersed samples decreased by 38 and 15%, respectively. This decrease could be explained due to weak interface between the fiber and the matrix. It is remarkable to mention that for the 5 layer hemp fiber reinforced samples, the ultimate stress was higher after water immersion because the swelled fibers filled the gaps between the fiber and the matrix. The tensile strain at failure for all wet specimens increased with respect to dry samples. This was explained by Dhakal due to “plasticization of hemp samples caused by moisture absorption.” Scanned electron microscope of immersed specimens showed that hemp fibers were not properly aligned leading to fiber entanglement. This in return resulted in the creation of voids and porosity due to the formation of areas full of resin. Mechanical properties dropped by the formation of voids which act as stress raisers.

2. Durability of natural fibers (without any polymer)

In a study by Ramakrishna and Sundararajan [21], natural fibers (coir, sisal, jute and Hibiscus cannabinus) were exposed to wetting and drying cycles and to continuous immersion for 60 days in three different mediums: fresh water, saturated lime, and a solution of sodium hydroxide. The W/D cycle consisted of 24 hours in wet environment, and then 24 hours drying at room temperature. After 60 days (30 cycles of wetting and drying), sisal and Hibiscus cannabinus were completely destroyed in saturated lime. Similarly, after both types of immersion in fresh water, the tensile strength of coir and sisal fibers was reduced about 40–50% and 30–40% respectively, while the tensile strength of jute and Hibiscus cannabinus was reduced about 80%. According to Ramakrishna, "the chemical dissolution is responsible for the loss in strength of the fibers and their efficiency as reinforcement."

Moisture studies on natural fibers including abaca, jute, hemp, sisal, flax, kenaf, and coir were conducted by Symington et al. [22]. Moisture plays an important role in affecting the mechanical properties of natural fibers. While some natural fibers retained their tensile strength when fully soaked to that of initial room temperature/humidity conditions, others showed a notable decrease in tensile strength.

3. Durability of natural fiber reinforced cementitious composites

Durability of natural fibers was previously studied by incorporating short discrete fibers into the concrete matrix. The durability of fiber reinforced concrete had been evaluated by Ramli et al. [23] by exposing the specimens to tropical climate, alternate wetting and drying, and seawater environment. It had been concluded that short coconut fibers improved the compressive strength of concrete specimens exposed to tropical climate by about 12%. The results also showed a maximum of 13% higher compressive strength than the control in alternate wet and dry conditions at 546 days. However, unpromising results were obtained in continuous seawater environment. Mohr et al. [24] studied the durability of kraft pulp fiber-cement composites exposed to wetting and drying cycles. Four percent reinforcement of kraft fiber was used in the cement matrix, and the composites were tested in flexure. Mohr et al. [24] concluded that three parts of degradation mechanism occurred. The first progress of degradation was “fiber–cement de-bonding up to 2 cycles”, the second part was “subsequent re-precipitation of hydration products within the void space at the former fiber-cement interface, prior to 10 wet/dry cycles”, and the third part of degradation was “fiber embrittlement due to mineralization, which appears to occur beyond 10 cycles.”

Many researchers studied the opportunity of improving the durability of natural fibers through pretreatment. Wei and Meyer [25] explored the case of improving degradation resistance of sisal fiber in concrete through fiber treatment. Two different treatment techniques were adopted: (1) Immersion in a Na_2CO_3 saturated solution for seven or ten days, and (2) thermal treatment in the oven for 8 hours at 150°C. Wetting and drying cycles were the adopted accelerated ageing procedure to determine the durability of sisal fiber reinforced concrete with recycled concrete aggregate. Both treatments improved the durability of sisal fiber reinforced concrete. In fact, both treatments had the potential of increasing splitting tensile strength and the compressive strength of concrete specimens after 30 wetting and drying cycles. Therefore, several treatments can be investigated to improve the degradation resistance of natural fibers. John et al. [26] explored the durability of 12 years old walls made up of coir fiber cementitious materials. Lignin had leached from the fibers; however, no major damage existed in the fibers in the external wall samples subjected to wetting and drying cycles. Similarly, Awwad et al. [27] investigated both the compressive strength and the splitting tensile strength of concrete reinforced with short hemp fiber at 1.5 years age. Hemp fibers did not have any negative effect on the mechanical properties of concrete. For example, the compressive strength of the control, polypropylene, and other ten different hemp mixes increased by about 61%, 47%, and 45-70%, respectively. Sivaraja and Kandasamy [28] studied the mechanical and micro-structural properties of fibrous concrete mix with coconut coir and sugarcane fibers at a volume fraction of 1.5%. The first part of this study consisted of exposing the concrete specimens to accelerated curing where the specimens were subjected to wetting and drying cycles continuously for 2 years. The second part dealt with durability studies. The concrete specimens were subjected to two different test methods for durability: (1) continuous immersion in sulfate for two years, and (2) freezing and thawing cycles. Coir and sugarcane fibers had the tendency to enhance the compressive strength, split tensile strength, modulus of rupture, and flexural performance at all curing ages. Fibrous specimens had almost no increase in compressive strength after 1 year curing while conventional concrete showed slight improvement. Regarding the split tensile strength, the modulus of rupture, and the flexural performance, there was no considerable difference over 2 years in both conventional and fibrous reinforced concrete. Scanned electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) analyses proved that a very good adhesion exists between the fibers and the matrix at the boundary of the transition zone. Conventional, coir fiber reinforced, and sugarcane fiber reinforced concrete had 54%, 68% and 74% loss in their compressive strength after 2 years of immersion in sulfate. Hence, unsatisfactory performance of natural fibers existed under sulfate attack. After freezing and thawing cycles, the relative modulus of elasticity of concrete decreased from 92% to 82% and 78% in coir and sugarcane fiber reinforced concrete, respectively. Thus, natural fibers gave acceptable results under freezing and thawing.

C. Durability studies on synthetic fibers

Durability studies on small-scale synthetic fiber confined columns are several; these studies tend to analyze the long term properties of these materials and come up with reduction factors to account for degradation when dealing with the mechanical properties of these strengthening materials. ACI (440.2R.08) [29] has indicated a reduction factor of 0.85 and 0.5 for carbon and glass fiber respectively under aggressive environment such as chemical plants and wastewater treatment plants. These durability considerations are essential to ensure the best performance of these composites. Ponmalar and Gettu [30] studied the durability of control, epoxy-coated, and glass fiber wrapped concrete when exposed to wetting and drying cycles and acidic attack for the period of 120 days. Epoxy coating will hinder the degradation at first stage, thus acting as a protective layer to the inside of the concrete. Moreover, the fiber wraps will resist degradation when exposed to environmental factors. The durability performance of confined concrete was better than both the control and epoxy-coated specimens. The strength reduction for wet/dry cycles and acidic exposure varied between 11-35% and 28-58% for both normal and high strength concrete, respectively. Catastrophic failure due to acidic attack was detected in the case of a single layer of glass fiber wrapped concrete. On the other hand, Micelli and Myers [31] reported an increase in terms of strength and ductility in FRP-wrapped cylinders. However, under environmental ageing and NaCL immersion (15% by weight) for 2,880 hours, a considerable reduction in strain was apparent. This is explained due to embrittlement of FRP system, resin damage, and chemical attack imposed on the fibers. This decrease in mechanical properties was much severe in the case of GFRP-wrapped cylinders than that of carbon. However, immersion of CFRP confined specimens in water, NaCl solution (5% by weight), and HCl solution for 2,000 hours resulted in no significant difference in ultimate compressive strength and strain with respect to control specimens. Toutanji and Yong [32] studied the durability of aramid FRP confined cylinders under wetting and drying cycles in seawater at 35°C for 75 days. The wet cycle was set to be 4 hours, while the dry cycle was 2 hours. Wet/dry cycles showed no effect on the strength of aramid-fiber cylinders. The compressive strength in the case of confined cylinder at room temperature was 150.5 MPa, while it was 150 MPa in the case of wet/dry exposure. However, the strength of concrete cylinders wrapped with aramid fiber showed a 7.9% decrease in compressive strength under freezing and thawing cycles.

In this research, similar tests were adopted to study the durability of concrete confined by one layer of hemp fiber bundles to compare its behavior with synthetic one.

CHAPTER III

MATERIALS AND METHODOLOGY

A. Pretreatment of hemp fibers

Each hemp-fiber bundle was made up of 3 treated hemp fibers twisted manually. Hemp-fiber bundle's diameter varied where it ranged between 0.8-2 mm. The hemp fibers were imported from Hemp-Traders, L.A., USA. These hemp fibers (Figure 1) were treated in sodium hydroxide NaOH solution at 6% by weight for 48 hours at room temperature, washed by water for about ten times afterwards, and then left to dry. Sodium hydroxide solution has the tendency to enhance the fiber–matrix bond. Alkali treatment eliminates all organic impurities leading to a rough clean surface, and consequently it increases the surface area of contact between hemp fibers and the resin as reported by Yan et al. [33]. Moreover, alkalization process can also reduce moisture absorption and so increase moisture durability by declining the hydrogen bonding capacity of cellulose and removing open hydroxyl groups that bond with water molecules [8]. No further treatment was performed afterwards.

Figure 1: Hemp fibers

B. Tensile testing of hemp-fiber bundles

1. Specimen preparation

Before testing, each hemp-fiber bundle was attached to a cardboard sheet from both sides to facilitate the process of testing. The hemp fiber was secured to the cardboard using epoxy and staples to assure that the hemp fiber will not be pulled out from the cardboard sheet. For each tensile test, the gauge length was taken 10 cm, and the fixity with the epoxy was set to be 5 cm on average. All tensile tests were conditioned at 20°C with a relative humidity of 60% before 1 week of testing.

Tensile testing was conducted on both uncoated and coated hemp-fiber bundles. Hemp-fiber bundles were coated with epoxy using the manual system (brush). Average tensile strength was calculated using the results of at least 5 specimens.

2. Test setup

The tensile testing was performed in accordance with ASTM D 3822 [34]. This test method is applicable to fibers removed from yarns, or from yarns processed further into fabrics. The tests were carried out using the universal testing machine shown in Figure 2. The samples were gripped using upper and lower pneumatic grips (Figure 3). The upper grip is connected to the load cell of 10 KN capacity. Tension force was applied to the hemp fiber at a rate of 15 mm/min and continued until the hemp-fiber bundle broke. The force-extension curve was plotted using a computer-aided program. According to the specifications, it is desirable to discard any result if the specimen slips at the jaws or breaks at the edge.

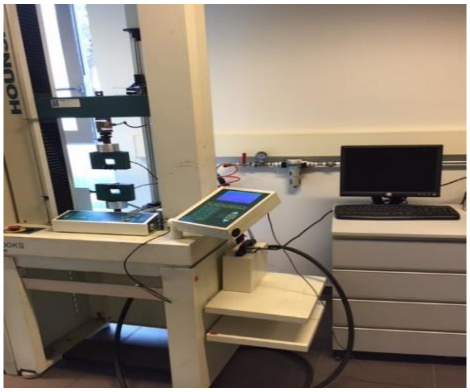


Figure 2: Testing machine with the computer-aided program

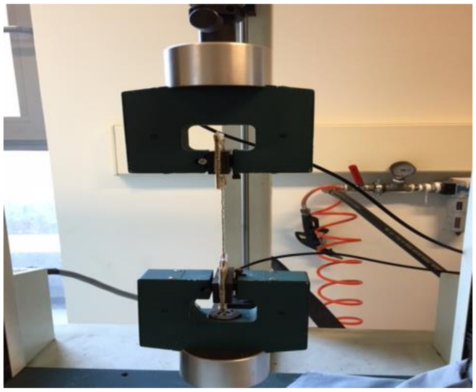


Figure 3: Tensile testing of hemp-fiber bundles

3. Fiber diameter measurement

The hemp fibers in this study are very variable in diameter along their length. This variability causes serious problems when it comes to tensile testing. Rao et al. [35] investigated the shape of the cross section of different natural fibers using optical laser beam equipment. The cross-section of all natural fibers may be estimated approximately as either circular or oval, with high variability in fiber diameter. The cross sectional area for tensile testing in the study by Rao et al. was determined by measuring the diameter using a digital micrometer with an average of 5 tensile tests for each fiber. A similar approach was used to measure the diameter in this study, but with a digital caliper with an accuracy of

0.01 mm. This is believed to be an appropriate method since the same procedure of measuring the diameter is applied for all hemp-fiber bundles.

Due to the high variable nature of the hemp fibers, the diameter was measured at 6 different positions along the fiber length. The cross sectional area used for the calculation of the tensile strength was obtained from the average diameter using the equation below:

$$A = \pi \frac{d_{average}^2}{4} \tag{1}$$

4. Experimental program

Tensile testing was conducted for two main reasons:

1. To study the variable nature of hemp-fiber bundles; this was done at the first stage before starting any durability test.
2. To predict the performance of hemp-fiber bundles at extended wet/dry cycles, and when continuously immersed in water and seawater. This was done after studying the durability of hemp-fiber confined concrete cylinders.

Thus, two different procedures were used to study the effect of epoxy coating and unprotected configuration on the tensile properties of hemp-fiber bundles:

1. Wetting and drying cycles (20 and 40 W/D cycles).
2. Prolonged exposure (1,800 hours).

The duration of the W/D cycle will be illustrated in the next part.

C. Compression testing of hemp-fiber confined concrete

1. Materials

a. <u>Concrete</u>

The concrete mix (Figure 4) used for casting concrete cylinders was prepared using a concrete mixer at the American University of Beirut (AUB). The target compressive strength of standard cylinders at 28 days was 22 MPa. The batching weights per cubic meter of concrete were: 880 kg of small coarse aggregate, 810 kg of sand, 400 kg of cement, and 280 kg of water. Ordinary Portland cement type 1 was used. Air content of the concrete was 0%. Concrete cylinders were left in a curing room and removed 1 day before being wrapped. The reported results mainly represent the average of 3 specimens.

Figure 4: Concrete pouring

b. Composite materials

Hemp-fiber bundles and epoxy resin were the two main components used to strengthen and reinforce concrete cylinders. The two-part epoxy resin consisted of main resin and a hardener with a mix ratio of 10:1 by weight.

2. Strengthening procedure

The concrete surface was cleaned of any dust before the hemp-fiber bundles were bonded on its surface. The hemp-fiber bundles were saturated with epoxy and were applied around the concrete surface in a continuous manner until the concrete cylinders were fully wrapped (Figure 5). An overlap of 150 mm was maintained. An outer layer of epoxy was applied on the surface of wrapped cylinders. The stress transfer from concrete to natural fiber polymers occurs through its interface; that is the adhesive epoxy layer. Thus, a good bond must be obtained between the hemp and the concrete. The concrete cylinders were left to cure 7 days before proceeding with any test. All cylinders including both wrapped and unwrapped were capped using 5 mm sulfur layer at both ends before testing.

Figure 5: Hemp-fiber confined concrete

3. Experimental program

A total of 42 concrete cylinders 9.5 cm diameter by 20 cm length were tested to failure in axial compression. The experimental program consisted of testing 36 plain concrete cylinders in two different environmental exposures. In each group, nine cylinders were wrapped with hemp-fiber bundles using the typical wet lay-up procedure, while nine others remained unwrapped and were therefore used for comparison purposes. The selected environmental conditions were:

1. Wetting and drying cycles using fresh water.
2. Wetting and drying cycles using seawater. The seawater was obtained from the Mediterranean Sea in Beirut (the proportion of salinity is about 3.5% on average).

The wetting procedure was maintained for 8 hours at room temperature laboratory conditions (Figure 6), followed by the drying cycle for 16 hours at the same conditions. Samples were exposed to 5, 10, and 20 wetting and drying cycles. Table 2 illustrates the test matrix.

The mechanical properties of the samples subjected to W/D cycles were compared to unconditioned ones (zero wet/dry cycles). It is important to note here that all samples were tested at the same time, regardless of the number of wet/dry cycles.

(a) (b)

Figure 6: Wetting cycle: (a) water, (b) seawater

Table 2: Test Matrix

Designation	Environmental Exposure
C	Control (unconditioned)
H	Hemp-fiber confined cylinder (unconditioned)
CW	Unconfined cylinder subjected to W/D cycles using water
HW	Hemp-fiber confined cylinder subjected to W/D cycles using water
CS	Unconfined cylinder subjected to W/D cycles using seawater
HS	Hemp-fiber confined cylinder subjected to W/D cycles using seawater

The number after CW, HW, CS, and HS represents the number of W/D cycles.

4. Compression testing

Compression testing was conducted using 4 LVDTs in the longitudinal direction using 200 tons capacity compression machine as shown in Figure 7. The concrete cylinders were tested according to ASTM C39 [36] at a constant rate of 0.2 MPa/s.

Figure 7: Cylinder setup

D. Statistical analysis

All test results were validated by statistical analysis focusing on the variable nature of hemp-fiber bundles. The means of all tested variables were compared to its control by Dunnett’s T-tests at a significance level of 0.05.

CHAPTER IV

EXPERIMENTAL RESULTS AND ANALYSIS

A. Variability of hemp-fiber bundles

The stress-strain curves of 22 uncoated hemp-fiber bundles are plotted in Figure 8. There is a significant range of variation between the lowest and the highest tensile strength. Figure 9, 10, 11 and 12 represent the corresponding diameter, tensile strength, modulus of elasticity, and strain at failure distribution respectively.

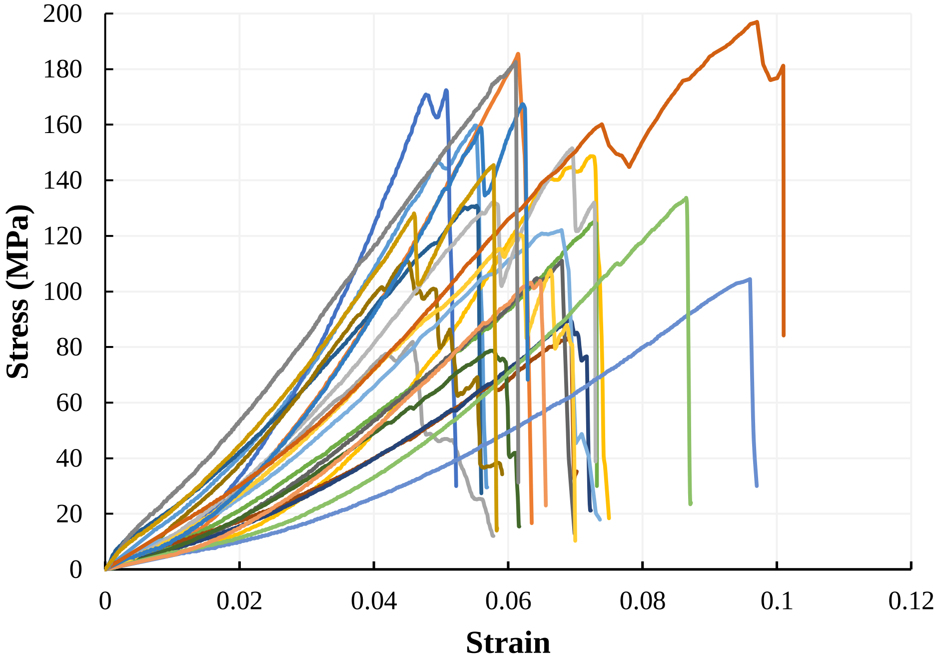


Figure 8: Stress-strain curves

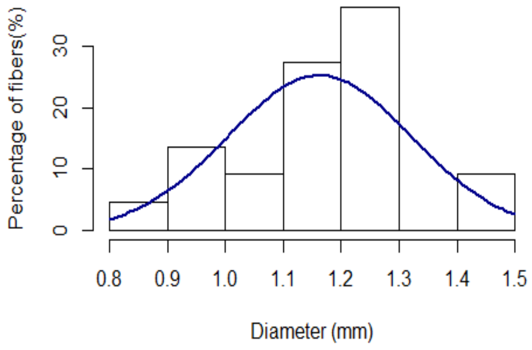


Figure 9: Diameter distribution

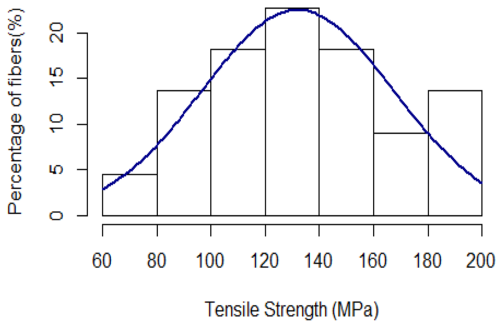


Figure 10: Tensile strength distribution

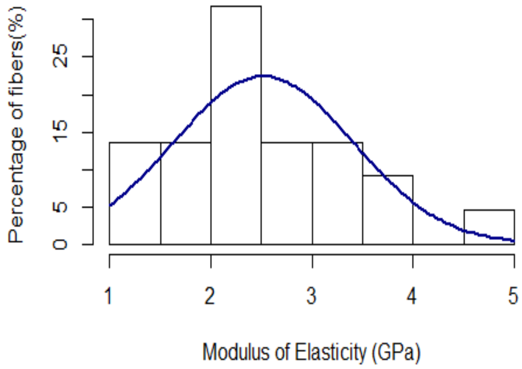


Figure 11: Modulus of elasticity distribution

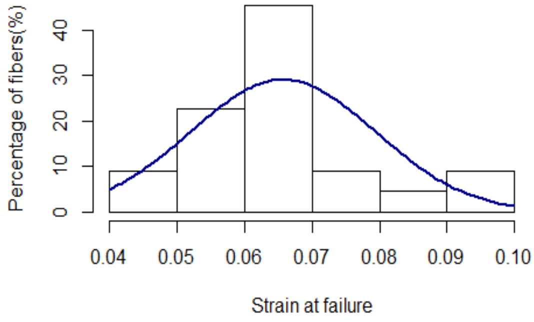


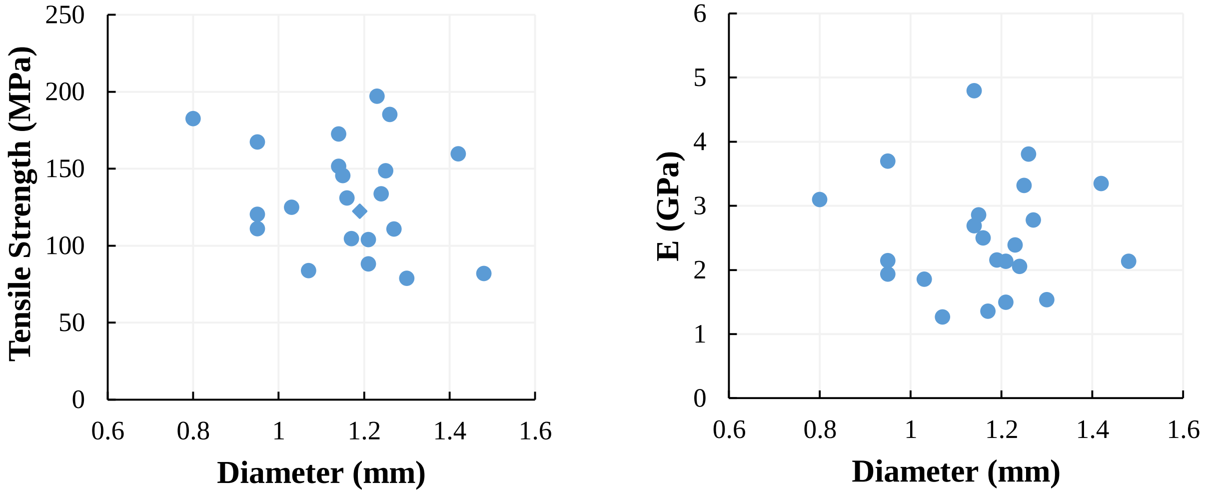
Figure 12: Strain at failure distribution

The mean diameter of hemp-fiber bundles is 1.16 mm, the average tensile strength of hemp-fiber bundles is 132 MPa, the average modulus of elasticity evaluated through the linear region of the stress-strain curve is 2.52 GPa, and the average strain at failure is 6.6% as reported in Table 3. As it was expected, the tensile stress is highly variable with a high standard deviation. The tensile strength of hemp-fiber bundle is less than that of a single hemp fiber which exhibits a tensile strength between 270 and 900 MPa [14]; this lower tensile strength is due to fraying of the specimen and not due to failure of the fibers as explained by Asprone et al. [37].

Table 3: Tensile properties of hemp-fiber bundles (uncoated)

	Diameter (mm)	Tensile failure stress (MPa)	Young's modulus (GPa)	Strain at failure (mm/mm)
Average	1.16	132.00	2.52	0.066
Standard deviation	0.16	35.47	0.89	0.014

The tensile strength and modulus of elasticity versus diameter are plotted in Figure 13. The curves could not be fitted linearly; thus, no significant relation exists between tensile strength and modulus of elasticity and diameter. The two mechanical properties vary for the same diameter indicating that the material variability is high.



(a) (b)

Figure 13: Tensile strength (a) and modulus of elasticity (b) versus diameter

1. Analysis of hemp-fiber bundles' failure

All hemp-fiber bundles failed in a brittle manner showing either linear elastic behavior or polynomial behavior. According to Sadek [38], three types of curves could be detected in the case of single hemp fiber. In the first case, the load increases linearly as the fiber is pulled until it reaches the peak load where the fiber breaks and load drops to zero. In the second case, the load increases in a polynomial matter rather than a linear one. While in the third case, the load increases in either a linear or polynomial matter, but when the hemp fiber breaks, it fails in a gradual pattern. During tensile testing, the fiber splits into multiple thin fibers that fail at different times, and the incompletely broken fibers still carry some load. Figure 14 depicts a hemp-fiber bundle close to failure.

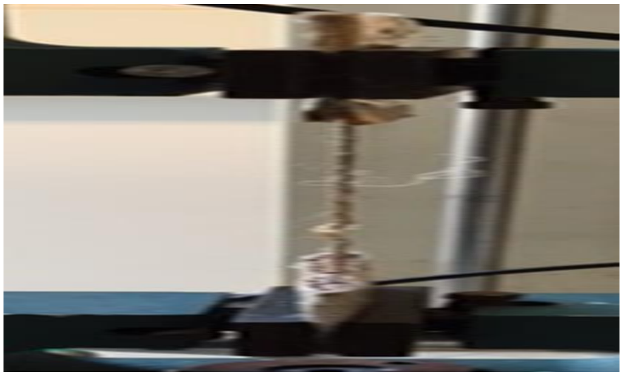
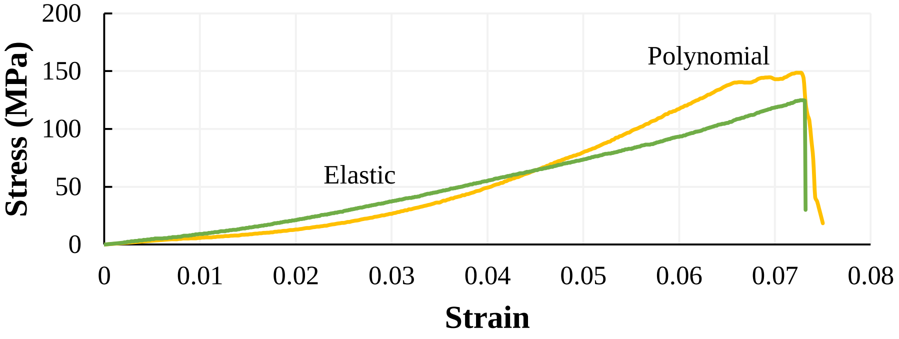


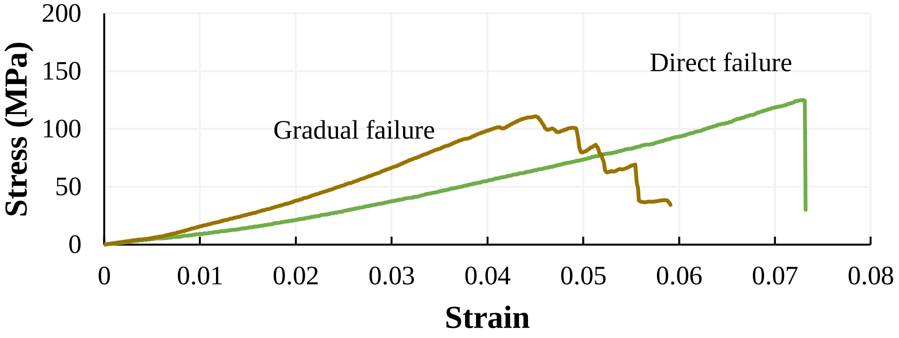
Figure 14: Hemp-fiber bundle close to failure

In fact, the three types of failure indicated above by Sadek et al. [38] were detected in the tested hemp-fiber bundles as shown in Figure 15. Almost all fibers failed in a polynomial behavior while only 10% of hemp-fiber bundles failed in a gradual manner. Variation of the stress-strain curve of flax natural fiber was also reported by Pickering et al.

[39] including linear elastic, plastic flow, and strain hardening. The initial non-linear portion of some of the stress-strain curves is mainly due to a collapse of the weak primary cell walls and delamination between fiber cells [40]. As stress is applied, micro-fibrils present in the cell walls which are aligned off-axis in the unstrained fiber become gradually reoriented in the axis of tension resulting in the phenomena of strain hardening that is reported above [41].



(a)



(b)

Figure 15: Typical stress-strain curves of hemp-fiber bundles: (a) elastic and polynomial curve, (b) sudden and gradual failure

2. Quantifying the variability of hemp fibers

The main disadvantage of using natural fibers in the construction industry is their variable nature. In fact, hemp-fiber bundles are assumed to reduce the scatter of results [25]. To quantify the degree of variability, Weibull statistics is used by many researchers. In this study, the form presented by Fidelis et al. [42] is used.

The probability of survival of a fiber at a stress σ is given by:

$$P(\sigma) = \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{2}$$

where σ is the fiber strength for a given probability of survival, and m is the Weibull modulus. σ_0 is defined as the characteristic strength, which corresponds to $P(\sigma) = 1/e = 0.37$

The fiber strengths are ranked according to the following estimator:

$$P(\sigma)_i = 1 - \frac{i}{N+1} \tag{3}$$

where $P(\sigma)_i$ represents the probability of survival corresponding to the ith strength value and N is the total number of tested fibers.

Eq.3 is substituted into Eq.2 yielding:

$$\ln\ln\left(\frac{N+1}{N+1-i}\right) = m \ln\left(\frac{\sigma}{\sigma_0}\right) \tag{4}$$

Plotting $\ln\ln\left(\frac{N+1}{N+1-i}\right)$ against $\ln\left(\frac{\sigma}{\sigma_0}\right)$ yields a straight line of slope m. The lower the value of m indicates the higher variability in strength.

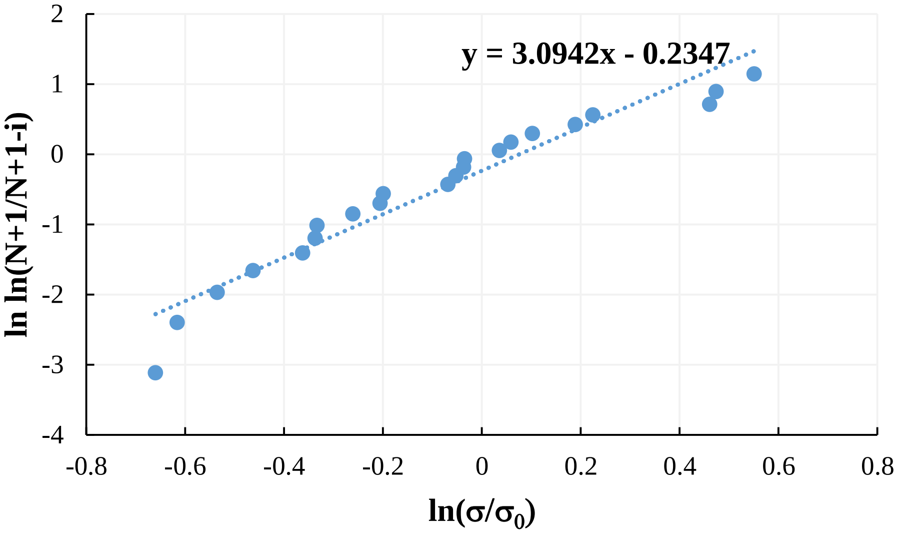


Figure 16: Weibull distribution for hemp-fiber bundles

The Weibull modulus (m=3.09 shown in Figure 16) determined by linear regression is in the same range as reported by Placet [43] for single hemp fibers (m=2.86 for a gauge length of 1 cm); the gauge length is greater in our study. The adopted 10 cm gauge length may increase the probability of defects along the fiber. Silva et al. [40] indicated an increase in Weibull modulus from 3 to 4.6 when decreasing the gauge length from 4 cm to 1 cm respectively. Thus, hemp-fiber bundles show a very similar behavior to single fibers in terms of variability.

Charlet et al. [44] explained this experimental scattering due to the difference in cellulose quantity from one flax fiber to other, and due to random distribution of defects along the length of the fiber. These defects arise during both "stem growth and extraction processes." According to Dittenber and GangaRao [14] in their critical review on the use of natural fibers in infrastructures, they stated that the variability of fibers can alter their quality and can cause problems in fiber reinforced polymers. This variability is due to many reasons: crop variety, seed density, soil quality, climate, harvest timing, variation of the cross sectional area of the fibers, extraction processing methods, and differences in drying processes. The same conclusion is valid here in the case of hemp-fiber bundles.

B. Durability studies

1. Effect of W/D cycles on mechanical properties of hemp-fiber confined concrete cylinders

a. Results from compression tests on cylinders

Results from the compression test of all tested cylinders are reported in Table 4 including the compressive strength of the three cylinders of each group, average compressive strength, and standard deviation. Figure 17 compares the compressive strength of the all tested specimens. The confinement of concrete cylinders by 1 layer of hemp-fiber bundles enhanced the compressive strength; the compressive strength increased from 33 MPa to 39.5 MPa that is about 19.7% on average.

The compressive strength of unwrapped cylinders after W/D cycles in both water and seawater solutions increased due to moist curing and further hydration of cement. 9.7, 26, and 16.4% increase in strength of unwrapped cylinders was reported after 5, 10, and 20 W/D cycles in water respectively. The increase in strength of unconfined cylinders after 5, 10, and 20 W/D cycles in seawater was 1.8, 17, and 12.1%, respectively. The increase in compressive strength seems to be more pronounced in water than in seawater. The compressive strength increased progressively after 5 and 10 cycles and then it decreased at 20 cycles. Similarly, Toutanji and Yong [32] reported 18% increase in compressive strength of control concrete cylinders after 75 days of wet/dry cycles in seawater.

On the other hand, there was no significant change in the compressive strength of wrapped cylinders subjected to W/D cycles. This slight increase or decrease was due to the variable nature of the hemp-fiber bundles. The drying cycle was conducted at room temperature which is less than the glass transition temperature of the epoxy; thus no epoxy deterioration was inspected. In fact, epoxy hinders the penetration of water/seawater into the hemp-fiber bundles causing neither degradation nor loss in confinement effectiveness.

Furthermore, it was observed that in almost all sets, there was one cylinder with a lower compressive strength than the remaining cylinders. This lower compressive strength was due to the voids under the sheets (hemp-fiber bundles in this case) that failed to provide the required confining pressure [45].

It is remarkable to note here that hemp-fiber confined concrete and plain concrete subjected to W/D cycles had approximately the same compressive strength. This was mainly due to the increase of compressive strength of control cylinders due to cement hydration. Thus, the one layer of hemp-fiber bundles gives advantageous results in terms of ductility rather than compressive strength.

Table 4: Summary of axial strength results of tested cylinders (f'_c in MPa)

W/D cycle number	Medium	Specimen	f'_c (1)	f'_c (2)	f'_c (3)	Average	SD
0	-	C	36.1	29.1	33.8	33.0	2.9
		H	42.1	39.3	37.0	39.5	2.1
5	water	CW-5	36.5	38.1	34.0	36.2	1.7
		HW-5	42.3	35.6	40.1	39.4	2.8
	seawater	CS-5	34.5	34.2	32.1	33.6	1.0
		HS-5	40.2	37.6	36.1	38.0	1.7
10	water	CW-10	40.5	42.7	41.5	41.6	0.9
		HW-10	38.2	36.0	38.5	37.6	1.1
	seawater	CS-10	35.2	37.6	42.9	38.6	3.2
		HS-10	41.4	44.2	39.7	41.8	1.8
20	water	CW-20	36.5	43.1	35.5	38.4	3.4
		HW-20	41.0	40.4	40.4	40.6	0.3
	seawater	CS-20	38.5	34.6	37.9	37.0	1.7
		HS-20	37.7	45.1	42.1	41.6	3.0

f'_c = maximum stress

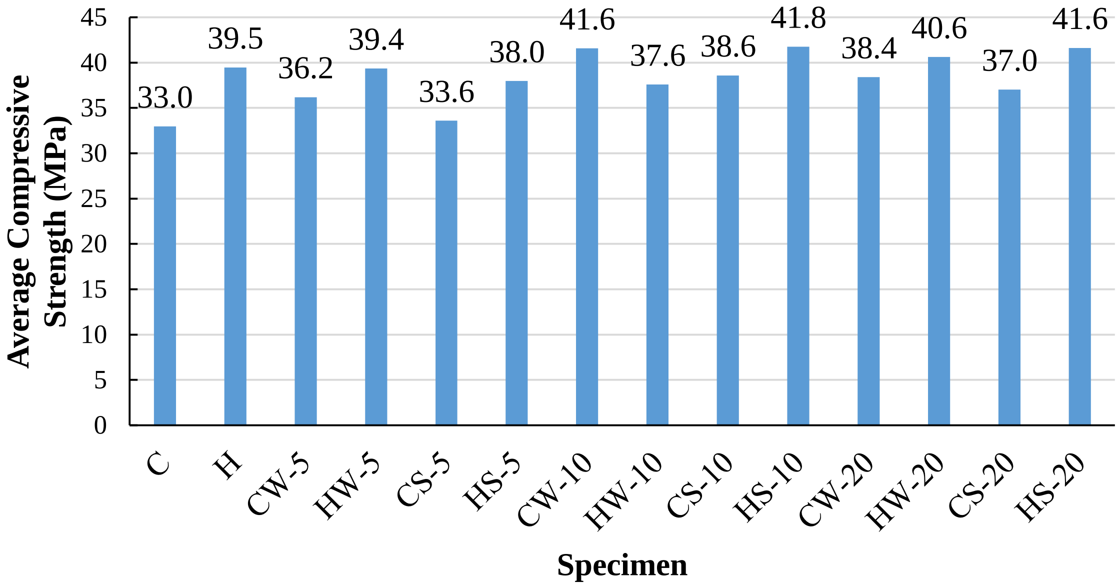
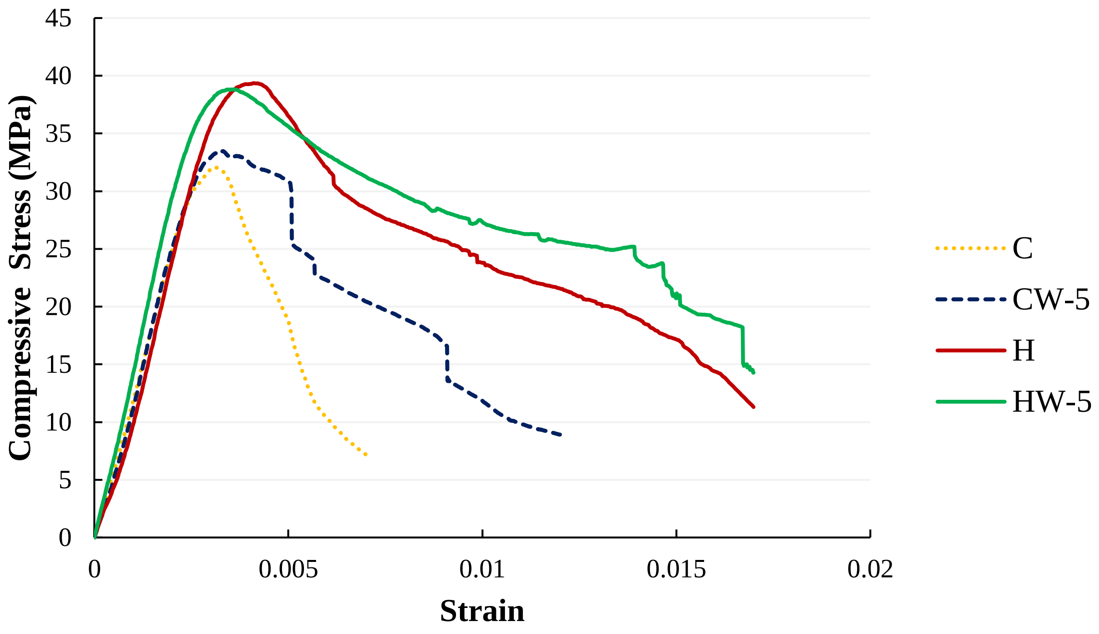


Figure 17: Comparison of average compressive strengths

b. Stress-strain curves

Stress-strain responses of confined and unconfined cylinders at different rates of wetting and drying cycles are shown in Figure 18. The strain represents the longitudinal strain obtained from the average of the 4 LVDTs readings for each specimen. Wetting and drying cycles had no effect on the nature of the stress-strain curve. As can be seen, concrete confined with hemp-fiber bundles shows similar behavior after W/D cycles in both water and seawater. The stress-strain curve of confined concrete is similar to the unconfined concrete featuring a post-peak descending branch.



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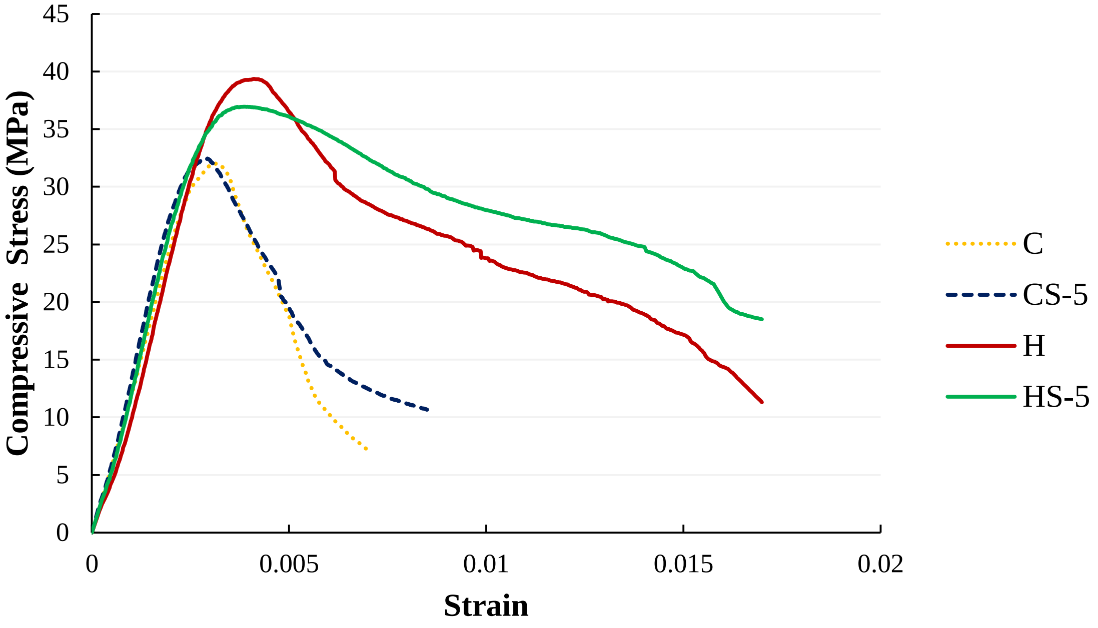
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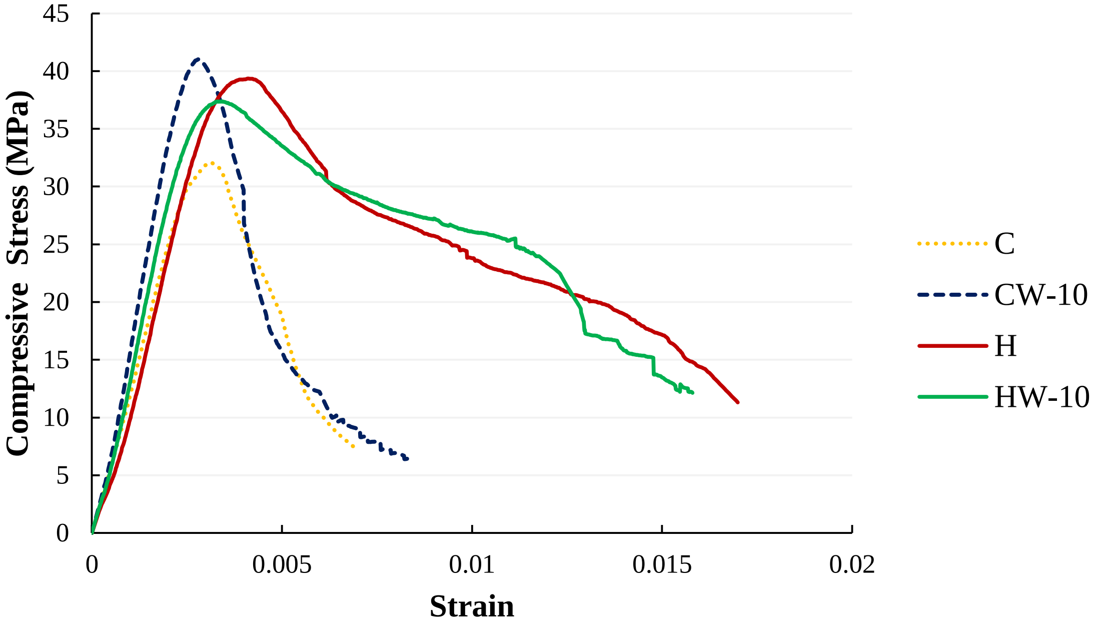
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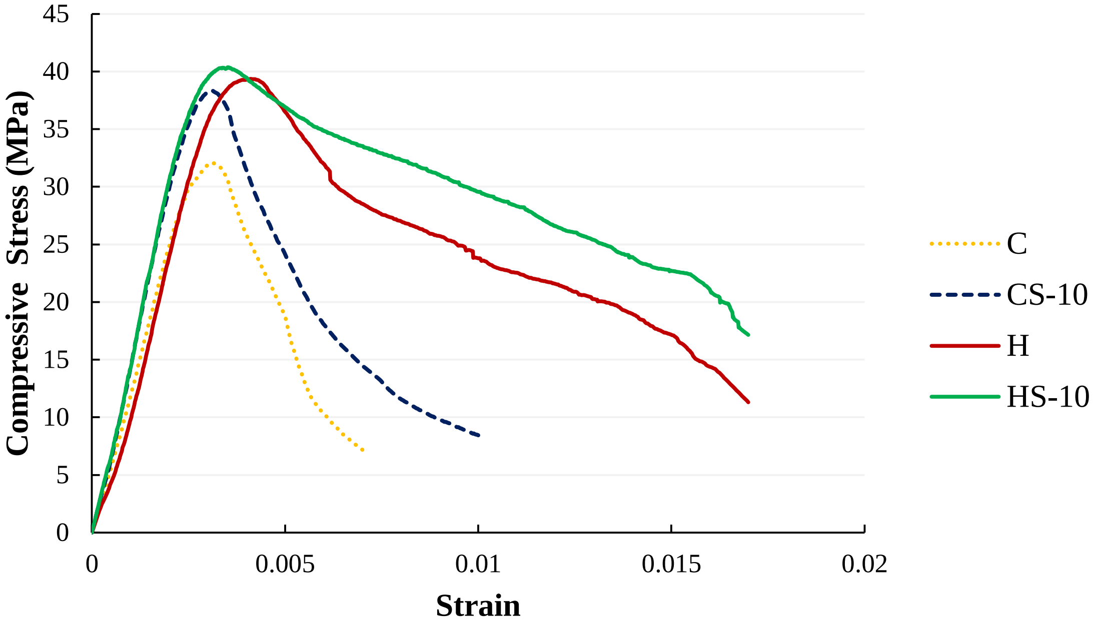

Compressive Stress (MPa)
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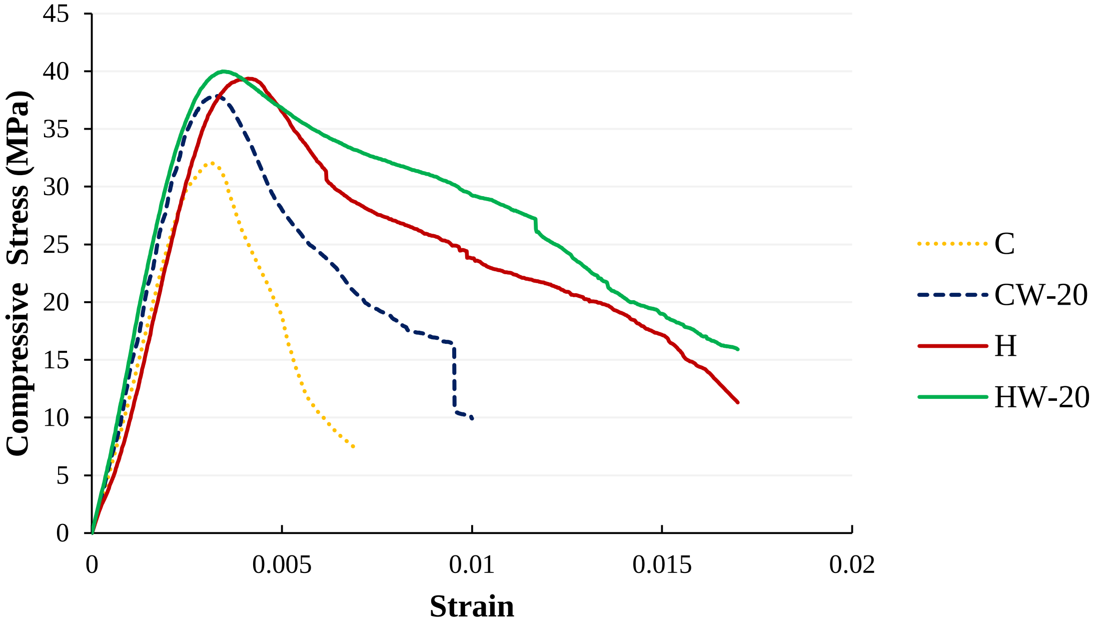
(d)



Compressive Stress (MPa)
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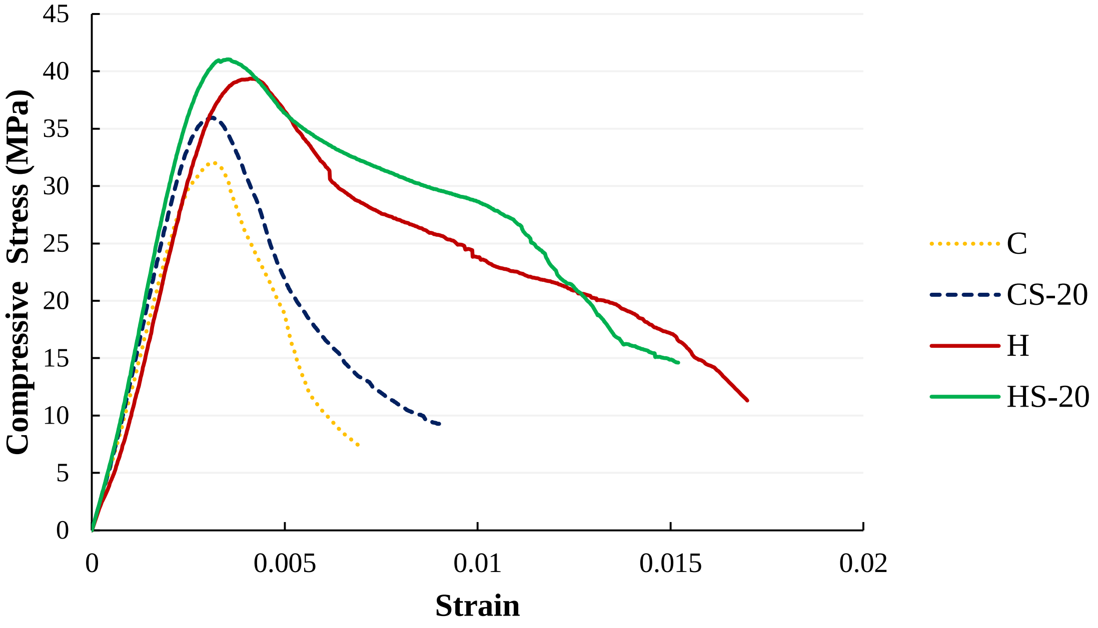
(e)



(f)

Figure 18: Stress-strain response of unwrapped and wrapped concrete in water and seawater at different rates of W/D cycles: (a) 5 W/D cycles in water, (b) 5 W/D cycles in seawater, (c) 10 W/D cycles in water, (d) 10 W/D cycles in seawater, (e) 20 W/D cycles in water, (f) 20 W/D cycles in seawater.

c. Effect of confinement

Confining concrete cylinders with hemp-fiber bundles enhanced the compressive strength, ductility, and energy absorption. However, the stress-strain response of hemp-fiber confined cylinders shows strain softening indicating low FRP ratio. This can be attributed to the fact that only one layer of hemp fiber is used. ACI code indicates a minimum confinement ratio f_l / f'_c of 0.08 (Appendix A). The confinement ratio is actually less than 0.08 which assures the nature of the stress-strain curve of hemp-fiber confined cylinders. The predicted compressive strength according to ACI Committee 440 is given in

Table 5. Little strength enhancement can be observed in the case of strain softening FRP-confined concrete; however, ductility improvement is observed. In fact, the maximum compressive strength is reached before FRP ruptures [46].

Table 5: Comparison of predicted ultimate strength of confined concrete

Cylinder Group	Experimental (MPa)	ACI(440) (MPa)	Error (%)
H	39.5	41.2	4.3

d. Energy absorption

Energy absorption is one of the significant deformational characteristics to determine the ductility of concrete structures [47]. Energy absorption is determined as the area under the stress-strain curve. Since the stress-strain curve of hemp-fiber confined concrete is very similar to that of plain concrete, but with a post ultimate ductile failure, and the point of zero load is not available, the area to be considered for comparison purposes is the elastic ascending portion and the descending one until 0.3 f'_c (Figure 19). This value of energy absorption is considered to be an acceptable arbitrary representation to only compare the behavior of the different stress-strain curves.

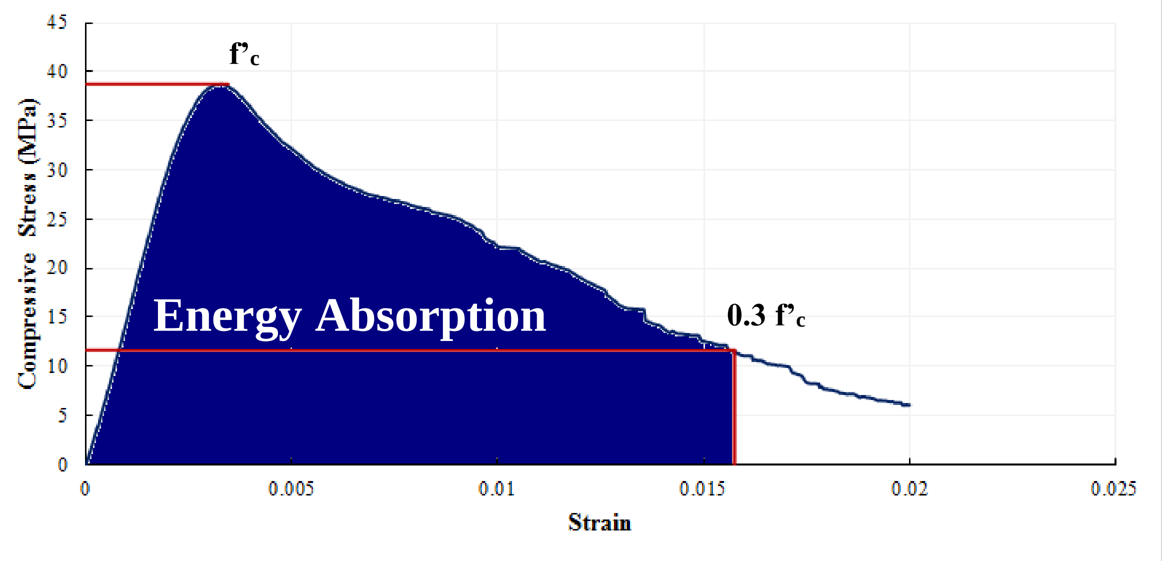


Figure 19: Energy absorption

Average energy absorption of unwrapped and wrapped cylinders is shown in Tables 6 and 7, respectively. For all hemp-fiber confined concrete, the stress-strain curve shows more toughness in terms of area under stress-strain curve with respect to control cylinders. There was no significant difference in relative improvement in energy absorption with respect to control (C) in all wrapped specimens subjected to wet/dry cycles at 0.05 significance level. This increase is again due to the variable nature of hemp fibers. However, unwrapped specimens subjected to wet/dry cycles showed higher energy absorption values; however, this improvement in energy absorption was not significant. This improvement in energy absorption can be attributed to the better performance of concrete when subjected to a prolonged duration of moisture.

Table 6: Average energy absorption of unwrapped cylinders

Average Energy Absorption (N m)			
Specimen	Average	SD	Relative improvement in E.A w.r.t control
C	173	17	1.00
CW-5	345	164	2.00
CW-10	259	111	1.5
CW-20	335	117	1.94
CS-5	293	198	1.69
CS-10	279	99	1.61
CS-20	247	93	1.43

Table 7: Average energy absorption of wrapped cylinders

Average Energy Absorption (N m)				
Specimen	Average	SD	Relative improvement in E.A w.r.t C[1]	Relative improvement in E.A w.r.t its control[2]
H	565	75	3.27	3.27
HW-5	674	42	3.90	1.95
HW-10	581	61	3.36	2.24
HW-20	683	171	3.95	2.04
HS-5	738	27	4.27	2.52
HS-10	774	56	4.48	2.78
HS-20	623	122	3.61	2.52

1: Unwrapped concrete cylinders subjected to 0 W/D cycles (C).

2: Unwrapped concrete cylinders subjected to 0, 5, 10, or 20 W/D cycles. Relative improvement in E.A w.r.t C, CW-5, CW-10, CW-20, CS-5, CS-10, and CS-20, respectively.

e. Failure mode

Figure 20 shows the failure mode of hemp-fiber confined concrete and plain concrete after the different proposed environmental exposures. Visual inspection of wrapped cylinders shows no severe damage with respect to control hemp-fiber confined cylinders. No epoxy deterioration is inspected. Cylinders wrapped with hemp-fiber bundles failed showing fiber rupture with cracking noises before failure. The failure was gradual and explosive and mainly occurred by concrete crushing at the middle of the tested cylinder. Fiber rupture occurred at different locations along the length of the concrete specimens. This is again attributed due to the variable nature of the hemp-fiber bundles that alters their quality. About 50% of hemp-fiber confined concrete failed by de-bonding when the hemp fibers failed. A layer of concrete remained attached to the failed hemp-fiber bundles indicating that the bond between concrete and hemp-fiber bundles was satisfactory. This de-bonding may be due to moisture effect. The unwrapped cylinders failed by concrete crushing and spalling. The general failure mode of unwrapped cylinders was concrete splitting. In fact, a network of large cracks was developed in concrete control specimens. In general, W/D cycles had no effect on the mode of failure of unwrapped and wrapped cylinders.

Figure 20: Failure modes of unwrapped and wrapped cylinders

f. Conclusion

Although hemp-fiber confined concrete was very similar to its treated control in terms of compressive stress, the hemp-fiber confined concrete still exhibits a significant post-ultimate ductile behavior with respect to its control. According to Balaguru and

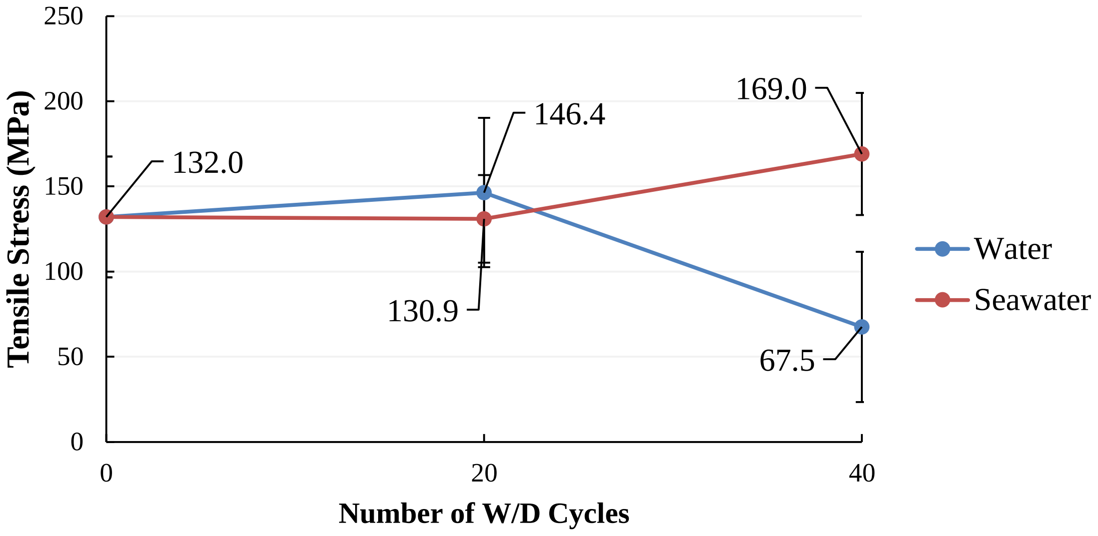
Toutanji [48], specimens wrapped with CFRP showed neither significant loss in strength nor ductility after 300 wet-dry cycles using salt water while GFRP cylinders experienced a slight reduction (the dry cycle was conducted at 35°C). Thus, despite the low number of wet/dry cycles conducted in this research, hemp-fiber confined concrete subjected to W/D cycles exhibited similar performance with respect to its control wrapped concrete.

2. Effect of W/D cycles and prolonged exposure on tensile strength and modulus of elasticity of hemp-fiber bundles

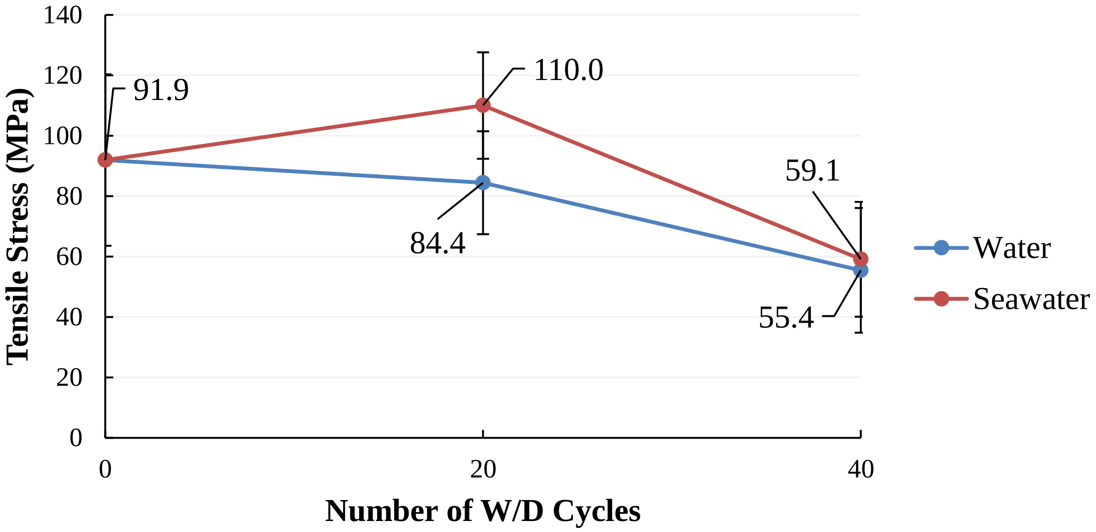
Tensile testing was conducted to predict the effect of wetting and drying cycles on uncoated and coated hemp-fiber bundles. 20 and 40 W/D cycles were used to study the performance of hemp-fiber bundles. The 20-cycle case is used to confirm the previous results of hemp-fiber confined concrete while the 40-cycle case is used to evaluate if hemp-fiber bundles get deterioated with extended degree of wetting and drying cycles. Moreover, both uncoated and coated hemp fibers were continiously immersed in water and seawater for 75 days. In fact, tensile testing was mainly conducted to study the effect of unprotected configuration and epoxy-coating on the tensile properties of hemp-fiber bundles.

a. Effect of W/D cycles and prolonged exposure on tensile stress

The average tensile strength of uncoated and coated hemp-fiber bundles after W/D cycles is illustrated in Figure 21. Figure 22 shows the effect of prolonged exposure to moisture. The typical stress-strain curves for all the specimens after W/D cycles and prolonged exposure are shown in Appendix B.



(a)



(b)

Figure 21: Effect of W/D cycles on tensile stress: (a) uncoated and (b) coated hemp-fiber bundles

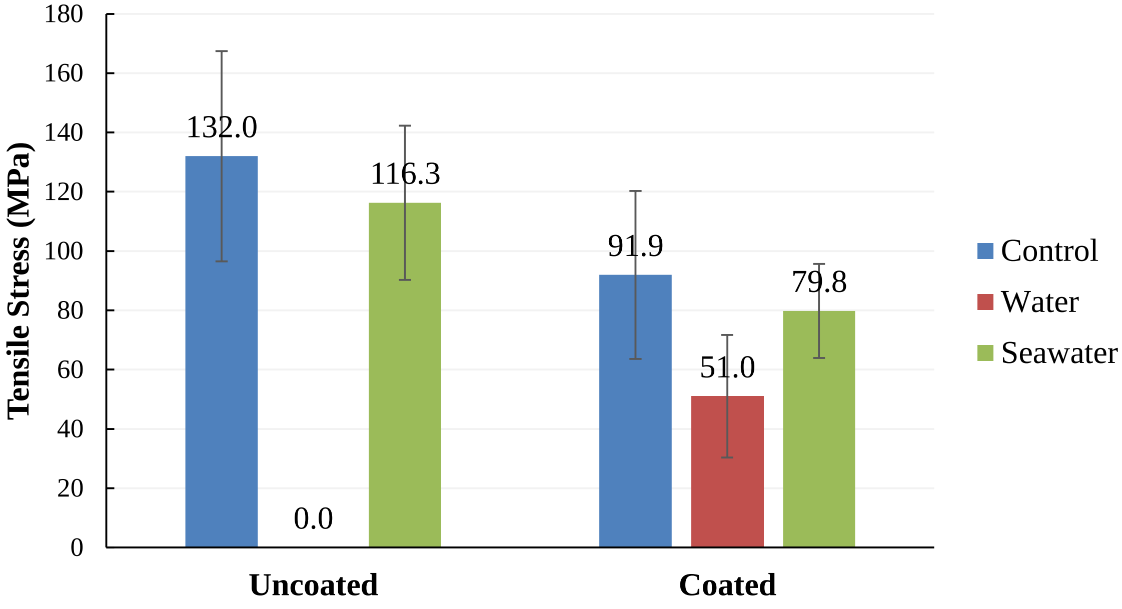


Figure 22: Effect of prolonged exposure on tensile stress

i. Uncoated hemp-fiber bundles

Effect of W/D cycles

After 20 cycles of W/D cycles using both water and seawater, there was no significant difference in tensile strength. However, after 40 W/D cycles in water, tensile strength decreased by about 49%, from 132 to 67.5 MPa; this decrease could be explained mainly due to reduction of cellulose content. In fact, cellulose, which is the major framework component in natural fibers, has a positive correlation with tensile strength and Young's modulus; tensile strength and Young's modulus of natural plant fibers increase with cellulose content [49]. However, after 40 W/D cycles using seawater, tensile strength was improved by about 28%, from 132 to 169 MPa.

Improving the mechanical properties of the bio-fiber composites using water and seawater treatment for 30 days had been studied by Leman et al. [50]. The improved composite tensile strength using treated sugar-palm fiber is due to the removal of the first layer of the fiber which leads to an enhanced adhesion quality between the fiber and the matrix. Similarly, Ishak et al. [51] reported improved impact and flexural strength of sugar palm fiber reinforced composites after soaking the fibers in seawater for 30 days due to improved surface characteristics of fibers. This result can justify the increase in tensile strength of hemp-fiber bundles after 40 W/D cycles using seawater. The removal of the first layer could be the reason behind the improvement of the tensile properties of the hemp fibers in seawater. W/D cycles in seawater of uncoated hemp-fiber bundles could cause removal of the weak layers such as pectin, lignin and wax that may not have been removed by NaOH treatment without causing any damage to cellulose cell.

Effect of prolonged Exposure

After 75 days of prolonged exposure to water, all hemp fibers were completely destroyed and could not be tested. On the contrary, hemp-fiber bundles resisted seawater deterioration where there was no significant change in tensile strength. It is good to note here that seawater constituents vary depending on the geographical [51]. Thus, the observed results highly depend on the source of seawater. Ramakrishna et al. [21] attributed this reduction in tensile strength after fresh water exposure due to microbiological action and chemical dissolution of cellulose, hemicellulose and lignin. However, in seawater, salt particles formed a coating around the surface of hemp fibers which hindered the penetration of water and prevented the damage caused by its effect. In a study by Symington et al. [22], single hemp fibers could not be tested after only 7 days of immersion in water. The seawater remained colorless and clean, while the color of fresh water changed to pale yellow and turbid implying the degradation of the constituents of the hemp fibers (Figure 23). Fungi growth was only detected on hemp-fiber bundles immersed in fresh water.

Figure 23: Prolonged exposure to water and seawater

ii. Coated hemp-fiber bundles

The tensile strength of hemp-fiber bundles with epoxy coating was less than the coated ones by about 30%. The tensile strength was 132 MPa and 91.9 MPa in the case of uncoated and coated hemp-fiber bundles respectively. This lower tensile strength is contrary to the literature where there was no significant difference in tensile strength between hemp-fiber bundles and coated hemp-fiber bundles with latex coating [37]. This lower tensile strength can be explained due to the effect of fiber orientation where uncoated hemp-fiber bundles are flexible and are perfectly oriented with the tensile loading.

Moreover, the creation of voids in the case of coated ones may lead to a lower tensile strength. Poor interfacial adhesion between the fiber and epoxy can also be a reason behind this lower tensile strength.

Effect of W/D cycles

After 20 cycles, no significant reduction in tensile strength was detected. However, a reduction up to 40% was detected after 40 W/D cycles. The tensile strength decreased from 91.9 MPa to 55.4 and 59.1 MPa in water and seawater respectively. The fiber/matrix interface is a critical area when considering moisture absorption. The reduction of the interactions between the fiber and the matrix leads to a reduction in the mechanical properties. This is mainly due to water diffusing in the composite creating hydrogen bonds [52]. Wei et al. [53] attributed the decrease in tensile stresses of basalt and glass FRP composites after seawater immersion to the generated voids and cracks of the resin allowing moisture to penetrate to the composite and as a result causing damage to the matrix, fiber, and interface.

One of the main disadvantages of using plant fiber is their unstable dimensional behavior. Internal stresses are generated in the structure when subjected to humid environment due to swelling [52]. Moisture absorption will plasticize the composites and consequently lead to reduction of the tensile strength, as reported by Joseph et al. [54]. Micro-cracks generated on the surface of coated hemp-fiber bundles limit the efficiency of stress transfer from epoxy to hemp-fiber bundles [11]. In fact, water uptake affects the matrix structure causing shrinkage and chain reorientation. Moreover, water absorption could also lead to the loss of compatibilization between the fibers and the matrix resulting in debonding and weakening of interface adhesion [55]. Thus, this reduction in tensile strength of coated hemp-fiber bundles after 40 cycles can be attributed to the damage of fiber/matrix interface, weak bond between hemp fiber and epoxy, and degradation of epoxy and fiber.

Effect of prolonged exposure

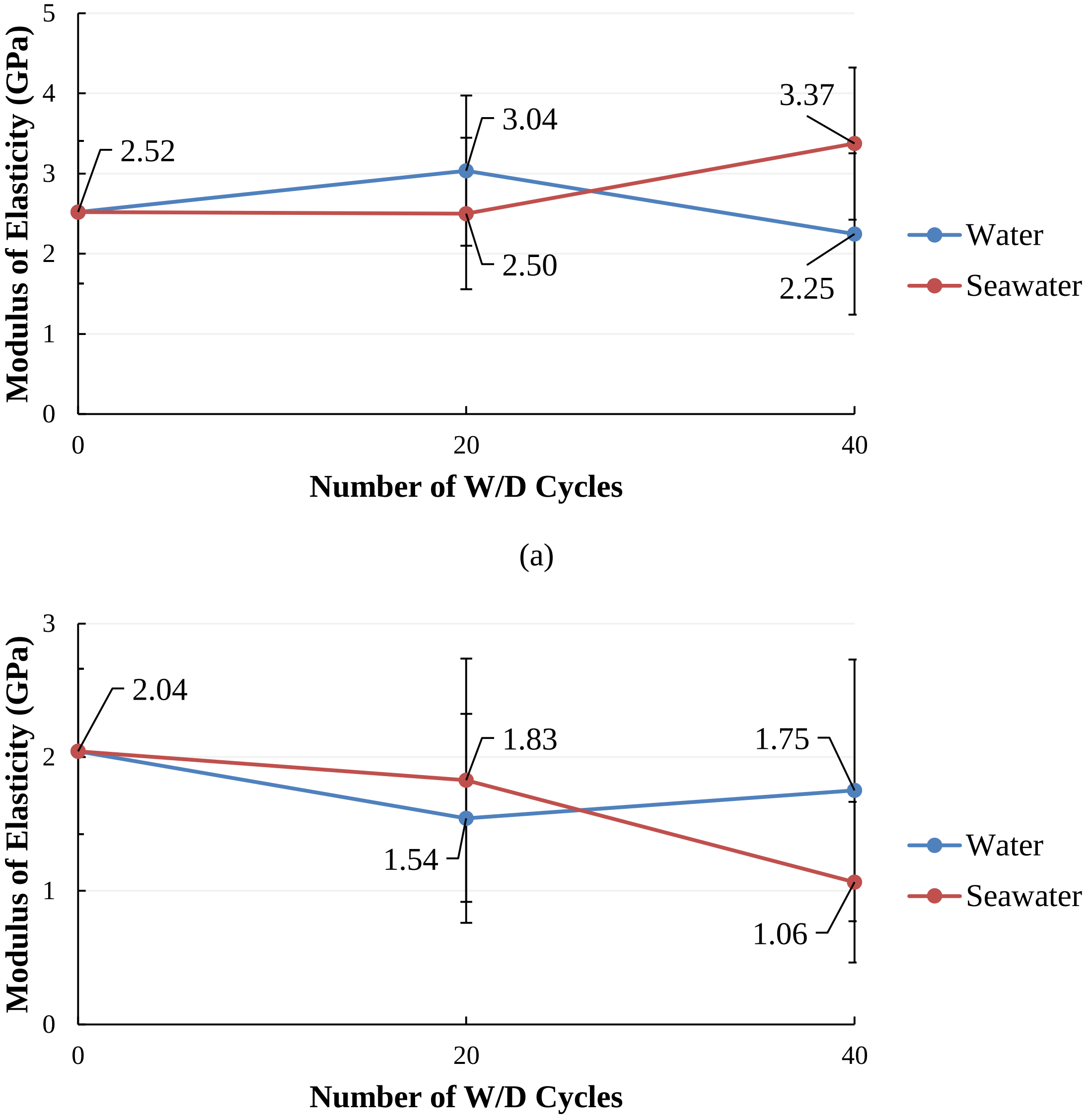
Epoxy coating protected hemp-fibers and prevented degradation to a certain extent where tensile strength decreased by about 45% after immersion in water for 75 days, from 91.9 MPa to 51 MPa. On the contrary, hemp-fibers with no epoxy coating were completely destroyed in water. Thus, epoxy coating plays a major role in preserving the tensile strength of hemp-fiber bundles.

Yan and Chouw [2] attributed the reduction in tensile strength of flax/epoxy composites after moisture exposure due to degradation of the flax fibers, the epoxy matrix, and the bond at the fiber/matrix interface. Chemical and physical degradation of the matrix is detected where moisture penetrates into the matrix leading to its breakdown. Thus, the same reasons behind the reduction in tensile strength after 40 W/D cycles are valid here after immersion in water.

Resistance to seawater degradation was apparent in the conservation of the tensile strength where no significant variation in tensile strength was observed after exposure to seawater. The tensile strength decreased only 13%, from 91.9 to 79.8 MPa. It seems that the effect of W/D cycles in seawater on tensile strength has a more pronounced effect than the effect of prolonged exposure.

b. <u>Effect of W/D cycles and prolonged exposure on modulus of elasticity</u>

The average modulus of elasticity of uncoated and coated hemp-fiber bundles after W/D cycles and prolonged exposure is illustrated in Figures 24 and 25, respectively.



(a)

(b)

Figure 24: Effect of W/D cycles on modulus of elasticity: (a) uncoated and (b) coated hemp-fiber bundles

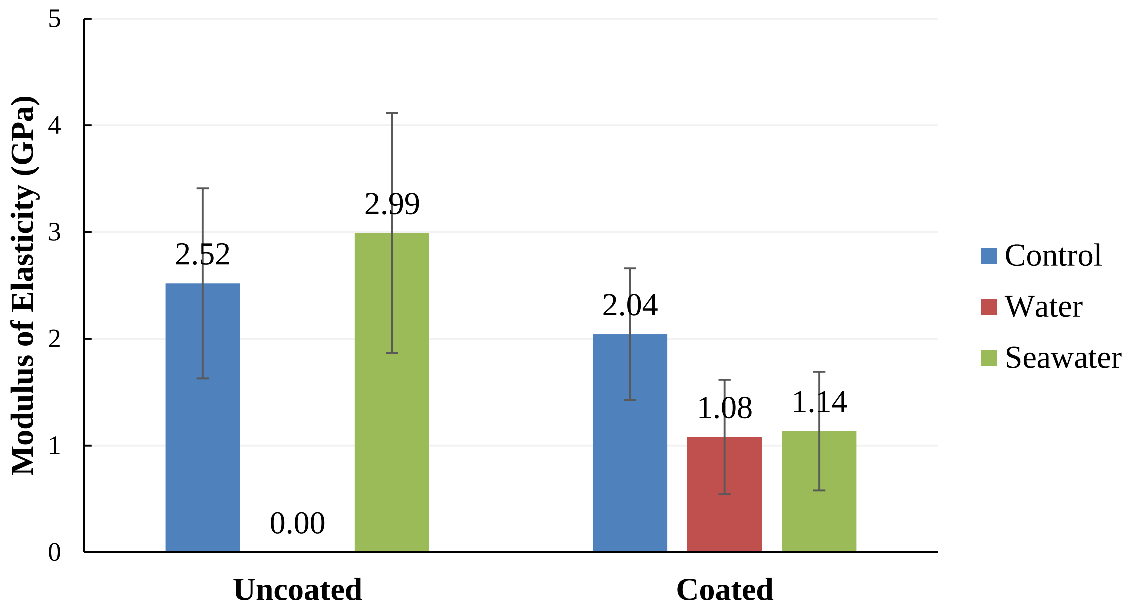


Figure 25: Effect of prolonged exposure on modulus of elasticity

i. Uncoated hemp-fiber bundles

From observing the results for Young's modulus of elasticity of uncoated hemp-fiber bundles, there was no significant difference in stiffness between control and specimens subjected to W/D cycles and prolonged exposure, except for hemp-fiber bundles continuously immersed in water where fibers were completely deteriorated. In fact, the difference was within standard deviation. This might be due to unusual patterns of behavior of fiber structure, and some internal fiber characteristics that maintain stiffness when exposed to moisture [22].

ii. Coated hemp-fiber bundles

Concerning the coated ones, there was no significant decrease in modulus after 20 W/D cycles in both water and seawater where tensile modulus decreased from 2.04 GPa to

1.54 and 1.83 GPa in water and seawater respectively, that is 25% and 10% decrease respectively. However, after 40 W/D cycles, the modulus decreased 14% in water, from 2.04 GPa to 1.75 GPa. The decrease in modulus was more pronounced in seawater with 48% reduction, from 2.04 GPa to 1.06 GPa.

After prolonged exposure, there was a significant degradation in tensile modulus. The largest reduction was for specimens immersed continuously in water with 47% reduction from 2.04 GPa to 1.08 GPa. Followed by specimens continuously immersed in seawater, the modulus decreased from 2.04 GPa to 1.14 GPa with a reduction of 44%.

CHAPTER V

CONCLUSION AND FUTURE RESEARCH

A. Summary

Natural fiber composites can be used as alternatives to glass or carbon fibers if it has proved it can satisfy the durability concerns. As waste materials at low cost and several environmental benefits, these environmentally friendly materials can be competitors to synthetic fiber reinforced polymers, and thus can be effectively used for strengthening and repair purposes of different concrete elements such as columns, beams, masonry walls, and bridges. The use of FRP composites has a significant increase in toughness which is a favorable for seismic strengthening. Nevertheless, environmental agents may degrade FRP materials, and so it will reduce its durability performance. Consequently, the implementation of natural fiber polymers use in the civil construction industry in the near future depends mainly on the knowledge of its behavior under different conditions to assure the structure’s safety concerns.

The experimental program carried in this study consisted of wetting and drying cycles in two different aqueous fluids “water and seawater” to oversee the short-term performance of natural-fiber wrapped cylinders and to analyze whether the effect of confinement has been altered by the simulated ageing procedure. Moreover, durability studies were conducted on uncoated and coated hemp-fiber bundles to comment on the effect of epoxy.

B. Conclusions

In spite of the fact that hemp fibers are very variable in their mechanical properties, some conclusions can be deduced from this study:

(1) Hemp-fiber bundles are proved to be effective external wrappings despite the fact that the increase in ductility was more pronounced than the increase in compressive strength. This was mainly due to the use of only one layer of hemp fibers.

(2) W/D cycles seemed to have no effect on the behavior of hemp-fiber confined concrete due to the good performance of epoxy.

(3) The chemical dissolution caused the tensile strength of uncoated hemp-fiber bundles to decrease. On the other hand, the improved fiber characteristics may be the reason behind the increased tensile strength after the 40 W/D cycles in seawater.

(4) The degradation of interface between epoxy and hemp led to lower mechanical properties in the case of coated hemp-fiber bundles.

(5) Prolonged exposure to water degraded hemp fibers completely. Meanwhile, epoxy-coating offered a suitable protected configuration. Resistance to seawater deterioration was apparent in the conservation of tensile stresses after prolonged exposure.

C. Recommendations for future research

(1) There is still a need to conduct long-term durability studies on hemp-fiber confined concrete; more wetting and drying cycles need to be performed to investigate the progress of damage.

(2) The effect of prolonged exposure on strength and confinement of natural fiber confined concrete needs to be explored.

(3) Uncertainty of the durability of hemp-fiber bundles due to its variable nature necessitates studying the durability of hemp fabric/epoxy composites which is used as a promising external strengthening material.

(4) The lower mechanical properties of coated hemp-fiber bundles with respect to uncoated ones necessitate investigating the option of using another type of epoxy that improves the composite quality.

Hence, studying the effect of environmental exposures on hemp fabric/epoxy composites is a significant way to investigate the effectiveness of strengthening plain concrete with renewable eco-friendly materials to come up with a more consistent conclusion.

Appendix I: ACI CODE

$f'_{cc} = f'_c + \psi_f\ 3.3\ \kappa_a f_l$

The maximum confining pressure f_l due to FRP jacket is calculated according to the following equation:

$f_l = \frac{2*Ef*n*tf*\varepsilon_{fe}}{D}$

The effective strain level in the FRP at failure ε_{fe} is given by:

$\varepsilon_{fe} = \kappa_\varepsilon\ \varepsilon_{fu}$

Ef is the tensile modulus of elasticity of FRP given by Hooke's law:

$Ef = f_{fu}/\varepsilon_{fu}$

where f_{fu}=design ultimate tensile strength of FRP given by:

$f_{fu} = C_e\ f^*_{fu}$

C_e=environmental reduction factor=0.85 for exterior exposure for FRP;

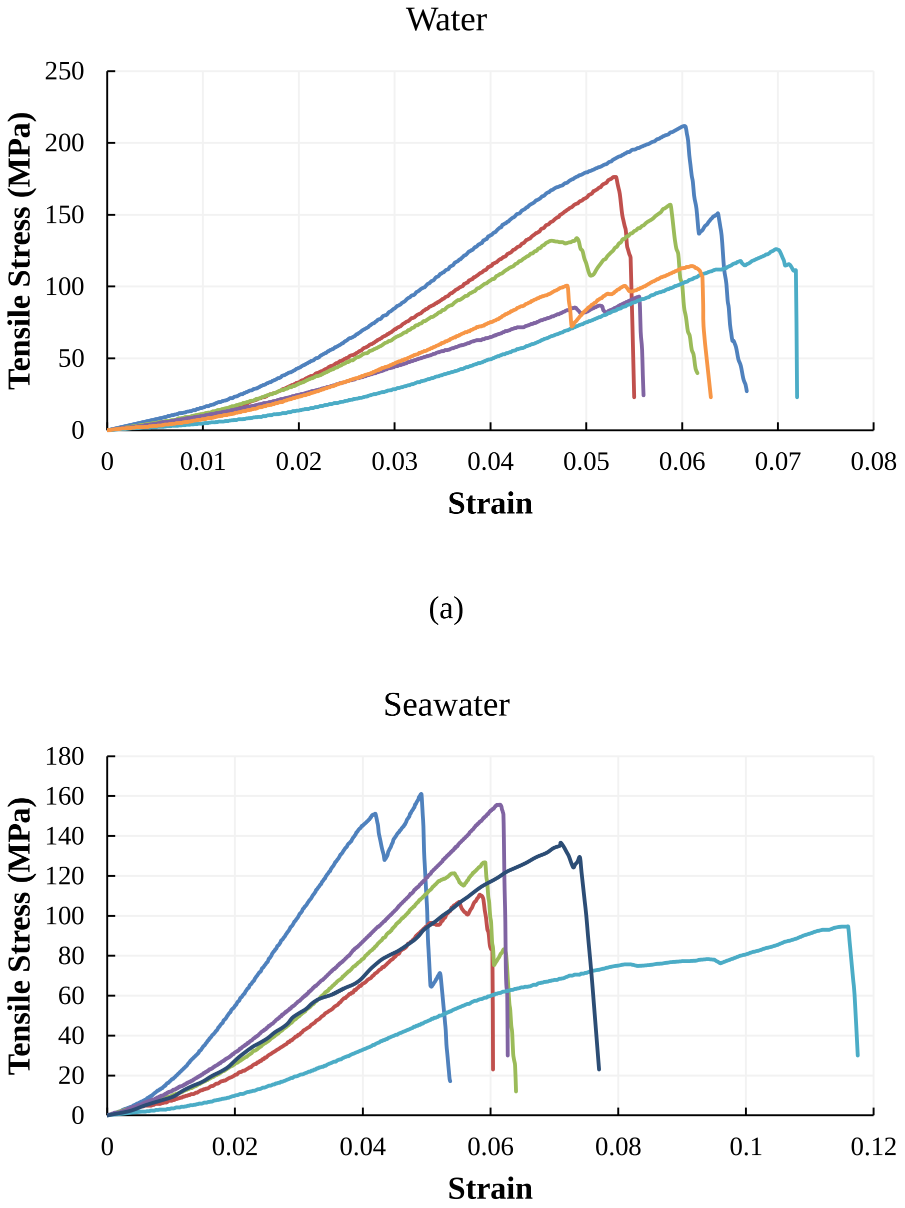
$f\ *_{fu}$ =ultimate tensile strength of FRP as reported by manufacturer; and ε_{fu}=design rupture strain of FRP given by:

$\varepsilon_{fu} = C_e\ \varepsilon^*_{fu}$

ε^*_{fu} =ultimate rupture strain of FRP as reported by manufacturer.

ψ_f =additional reduction factor=0.95; κ_a=efficiency factors that account for the geometry of the section=1.0 for circular cross section, n=number of fiber reinforced polymer layers; t_f=thickness of the fiber reinforced polymer layer; D =diameter of the concrete cylinders; A strain efficiency factor κ_ε of 0.55 and a minimum confinement ratio $f_l\ /f'_c$ of 0.08 should be taken to assure a non-descending second branch in the stress-strain performance.

Appendix II: Stress-strain curves

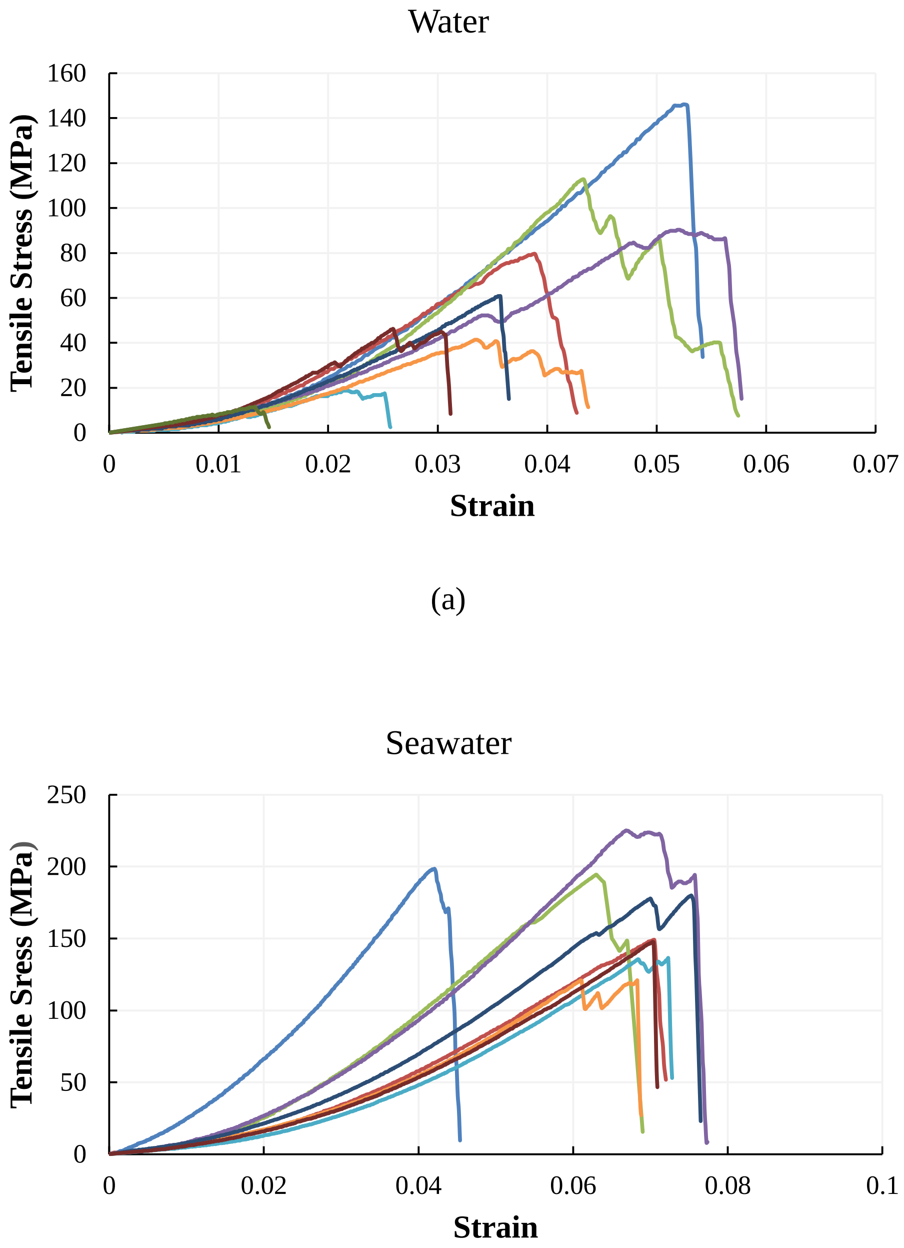


(a)

(b)

Figure 26: Stress-strain curves of uncoated hemp-fiber bundles after 20 W/D cycles:

(a) water, (b) seawater



(a)

(b)

Figure 27: Stress-strain curves of uncoated hemp-fiber bundles after 40 W/D cycles:

(a) water, (b) seawater

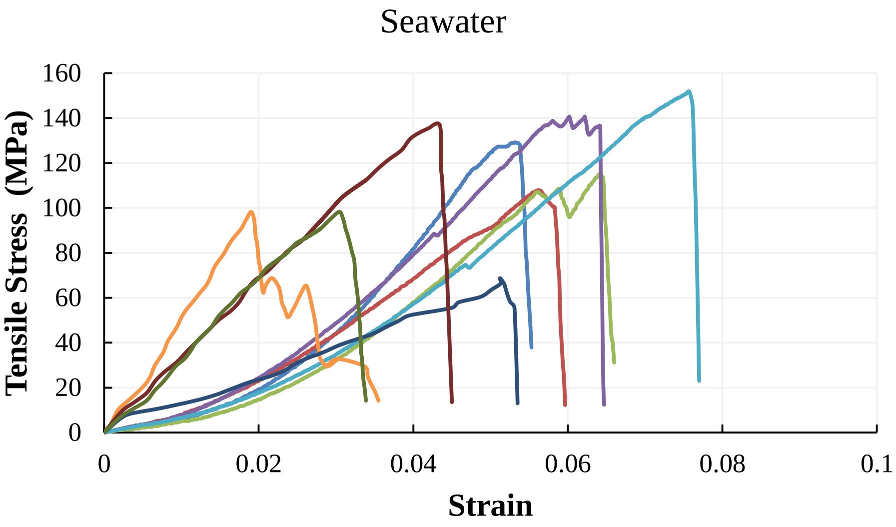


Figure 28: Stress-strain curves of uncoated hemp-fiber bundles after prolonged exposure to seawater

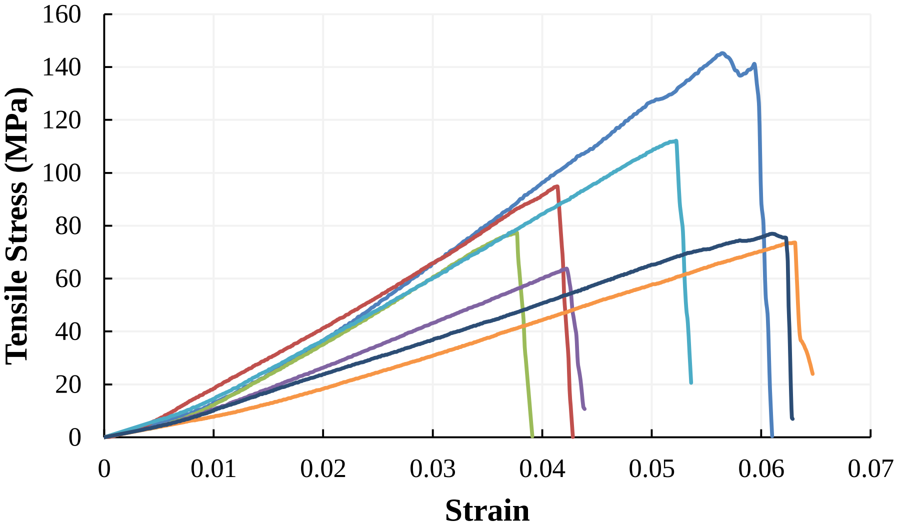
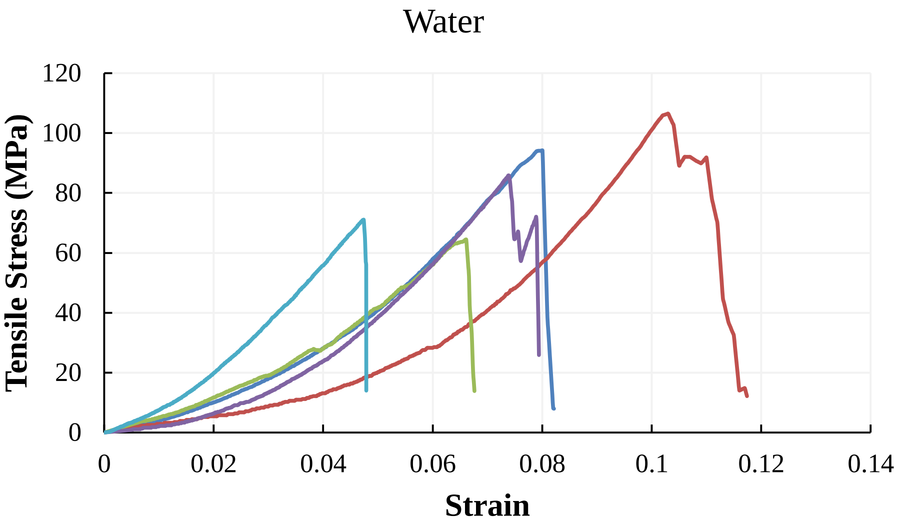
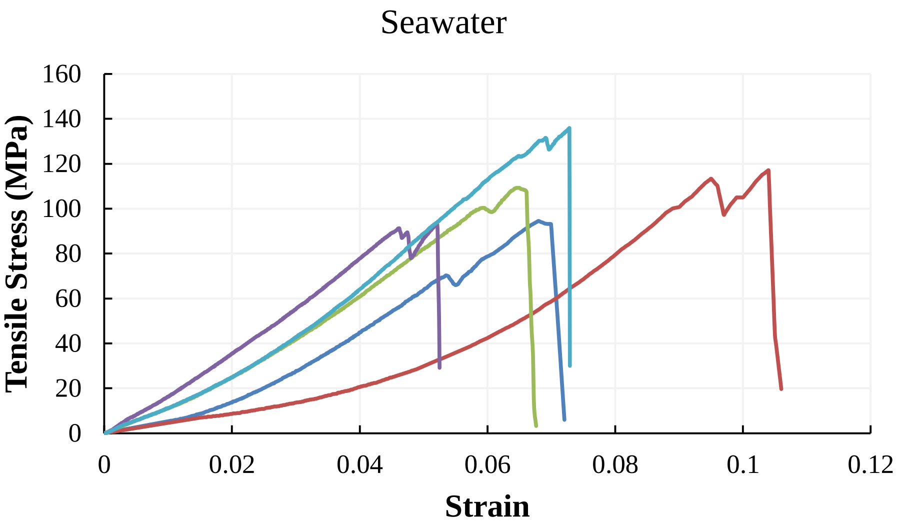


Figure 29: Stress-strain curves of coated hemp-fiber bundles (control)



(a)



(b)

Figure 30: Stress-strain curves of coated hemp-fiber bundles after 20 W/D cycles:

(a) water, (b) seawater

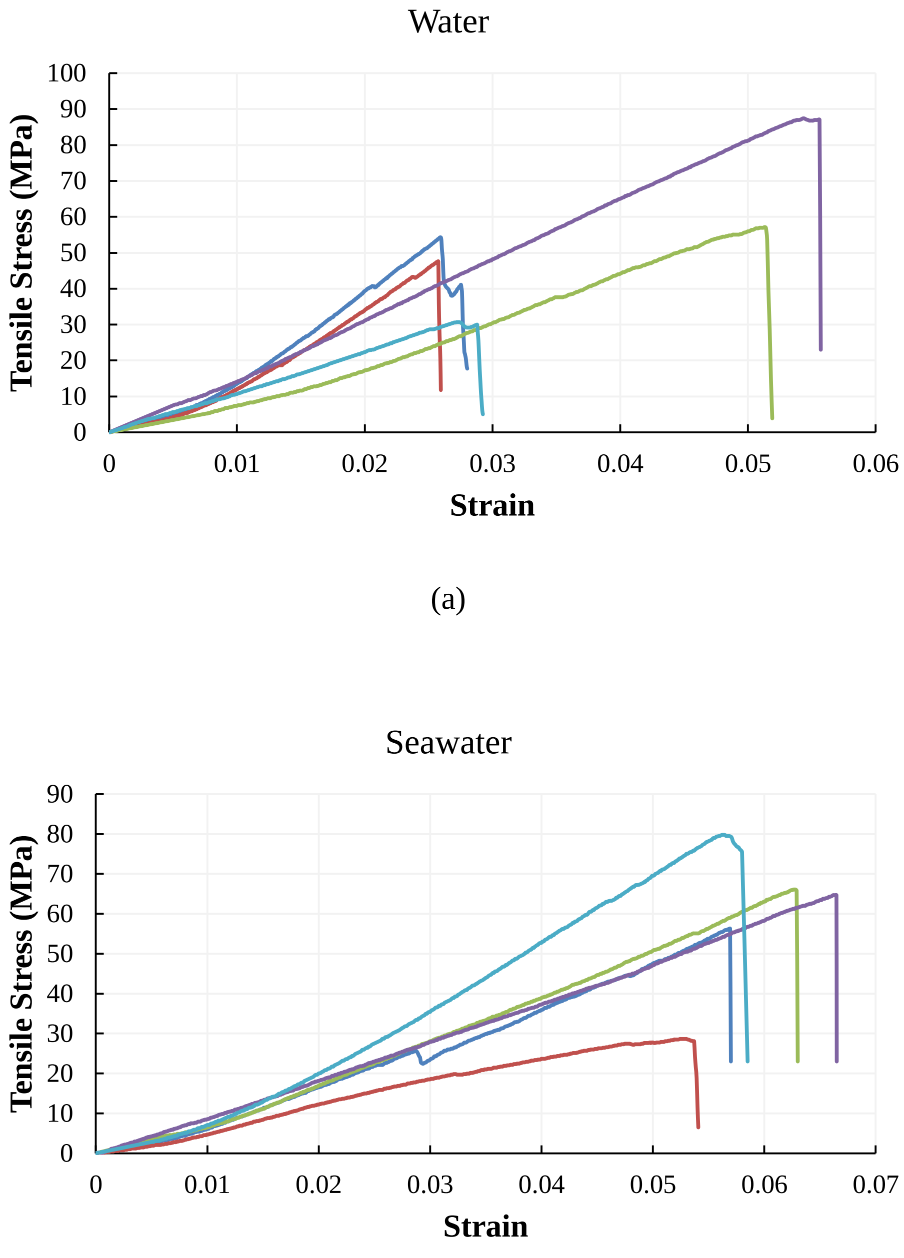
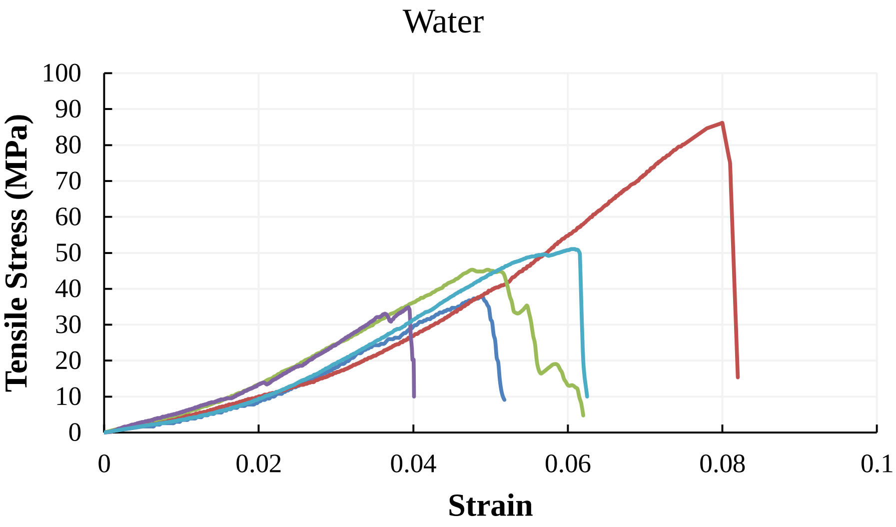
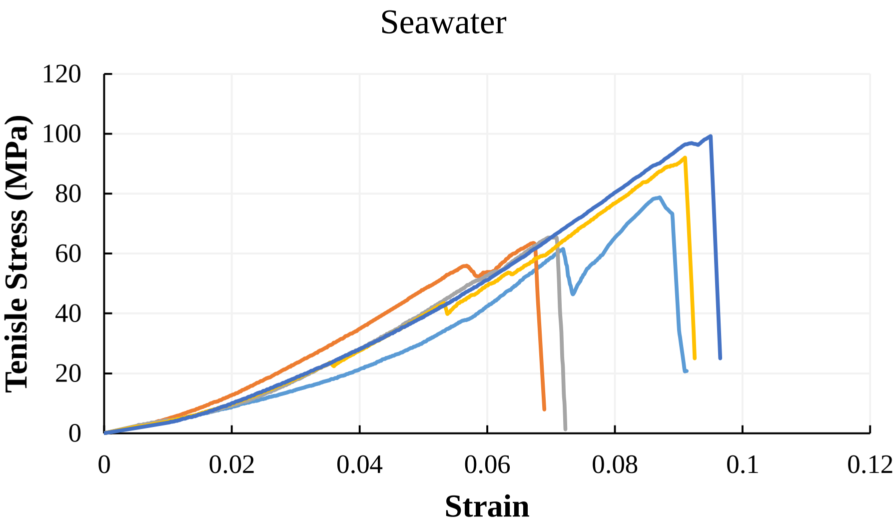


Figure 31: Stress-strain curves of coated hemp-fiber bundles after 40 W/D cycles:

(a) water, (b) seawater



(a)



(b)

Figure 32: Stress-strain curves of coated hemp-fiber bundles after prolonged exposure:

(a) water, (b) seawater

Bibliography

[1] L. Yan, B. Kasal and L. Huang, "A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering," *Composites Part B,* vol. 92, pp. 94-132, 2016.

[2] L. Yan and N. Chouw, "Effect of water, seawater and alkaline solution ageing on mechanical properties of flax fabric/epoxy composites used for civil engineering applications," *Construction and Building Materials,* vol. 99, pp. 118-127, 2015.

[3] A. K. Bledzki and V. E. Sperber, Natural and wood fibre reinforcement in polymers, 1st ed., iSmithers Rapra Publishing, 2002.

[4] L. Yan, "Plain concrete cylinders and beams externally strengthened with natural flax fabric reinforced epoxy composites," *Materials and Structures,* vol. 49, no. 6, p. 2083–2095, 2015.

[5] L. Yan, N. Chouw and K. Jayaraman, "Flax fibre and its composites - A review," *Composites Part B,* vol. 56, pp. 296-317, 2014.

[6] D. Saheb and J. Jog, "Natural Fiber Polymer Composites. A Review," *Advances in Polymer Technology,* vol. 18, no. 4, p. 351–363, 1999.

[7] A. Shahzad, "Hemp fiber and its composites – a review," *Journal of Composite Materials,* vol. 46, no. 8, pp. 973-986, 2012.

[8] Z. N. Azwa, B. F. Yousif, A. C. Manalo and W. Karunasena, "A review on the degradability of polymeric composites based on natural fibres," *Materials & Design,* vol. 47, pp. 424-442, May 2013.

[9] D. Hristozov, L. Wroblewski and P. Sadeghian, "Long-term tensile properties of natural fibre-reinforced polymer composites: Comparison of flax and glass fibres," *Composites Part B,* vol. 95, pp. 82-95, 2016.

[10] T. Sen and A. Paul, "Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP," *International Journal of Sustainable Built Environment,* vol. 4, no. 2, pp. 248-264, 2015.

[11] L. Yan, N. Chouw and K. Jayaraman, "Effect of UV and water spraying on the mechanical properties of flax fabric reinforced polymer composites used for civil engineering applications," *Materials & Design,* vol. 71, pp. 17-25, 2015.

[12] "International Year of Natural Fibres 2009," [Online]. Available: http://www.naturalfibres2009.org/. [Accessed 29 September 2016].

[13] "General Hemp Information," [Online]. Available: http://www.hempbasics.com/shop/hemp-information. [Accessed 30 September 2016].

[14] D. B. Dittenber and H. V. S. GangaRao, "Critical review of recent publications on use of natural composites in infrastructure," *Composites Part A: Applied Science and Manufacturing,* vol. 43, no. 8, pp. 1419-1429, 2012.

[15] A. Shahzad, "Effects of water absorption on mechanical properties of hemp fiber composites," *Polymer Composites,* vol. 33, no. 1, pp. 120-128, 2012.

[16] H. Wang, G. Xian, H. Li and L. Sui, "Durability study of a ramie-fiber reinforced phenolic composite subjected to water immersion," *Fibers and Polymers,* vol. 15, no. 5, pp. 1029-1034, 2014.

[17] L. Yan, S. Su and N. Chouw, "Microstructure, flexural properties and durability of coir fibre reinforced concrete beams externally strengthened with flax FRP composites," *Composites Part B: Engineering,* vol. 80, pp. 343-354, 2015.

[18] A. Michel and S. Billington, "Characterization of poly-hydroxybutyrate films and hemp fiber reinforced composites exposed to accelerated weathering," *Polymer Degradation and Stability-Journal,* vol. 97, no. 6, pp. 870-878, 2012.

[19] B. Singh, M. Gupta and A. Verma, "The durability of jute fibre-reinforced phenolic composites," *Composites Science and Technology,* vol. 60, no. 4, pp. 581-589, 2000.

[20] H. Dhakal, Z. Zhang and M. Richardson, "Effect of water absorption on the mechanical properties of hemp fiber reinforced unsaturated polyester composites," *Composites Science and Technology,* vol. 67, no. 7, pp. 1674-1683, 2007.

[21] G. Ramakrishna and T. Sundararajan, "Studies on the durability of natural fibers and the effect of corroded fibers on the strength of mortar," *Cement and Concrete Composites,* vol. 27, no. 5, p. 575–582, 2005.

[22] M. C. Symington, W. M. Banks, O. D. West and R. A. Pethrick, "Tensile testing of cellulose based natural fibers for structural composite applications," *Journal of Composite Materials,* vol. 43, no. 9, pp. 1083-1108, 2009.

[23] M. Ramli, W. Kwan and N. Abas, "Strength and durability of coconut-fiber-reinforced-concrete in aggressive environments," *Construction and Building Materials* , vol. 38, pp. 554-566, 2013.

[24] J. Mohr, H. Nanko and K. V. Kurtis, "Durability of kraft pulp fiber–cement composites to wet/dry cycling," *Cement and Concrete Composites,* vol. 27, no. 4, pp. 435-448, 2005.

[25] J. Wei and C. Meyer, "Improving degradation resistance of sisal fiber in concrete through fiber surface treatment," *Applied Surface Science,* vol. 289, p. 511–523, 2014.

[26] V. John, C. Cincotto, V. Agopyan and C. Oliveira, "Durability of slag mortar reinforced with coconut fiber," *Cement and Concrete Composites,* vol. 27, no. 5, pp. 565-574, 2005.

[27] E. Awwad, B. Hamad, M. Mabsout and H. Khatib, "Long Term Strength Behavior of Hemp-Concrete," 2014.

[28] M. Sivaraja and S. Kandasamy, "Study on durability of natural fiber concrete composites using mechanical strength and microstructural properties," *Bulletin of Materials Science,,* vol. 33, no. 6, p. 719–729, 2010.

[29] ACI Committe 440, "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures," American Concrete Institute, Detroit, 2008.

[30] V. Ponmalar and R. Gettu, "Durability Studies on Confined Concrete using Fiber Reinforced Polymer," *Journal of The Institution of Engineers (India): Series A,* vol. 95, no. 2, pp. 91-96, 2014.

[31] F. Micelli and J. Myers, "Durability of FRP-confined concrete," *Proceedings of the Institution of Civil Engineers - Construction Materials,* vol. 171, no. 4, pp. 173-185, 2008.

[32] H. Toutanji and D. Yong, "Strength and durability performance of concrete axially loaded members confined with AFRP composite sheets," *Composites Part B: Engineering,* vol. 33, no. 4, p. 255–261, 2002.

[33] L. Yan, N. Chouw and X. Yuan, "Improving the mechanical properties of natural fibre fabric reinforced epoxy composites by alkali treatment," *Journal of Reinforced Plastics and Composites,* vol. 31, no. 6, pp. 425-437, 2012.

[34] American society for testing and materials, "Standard Test Method for Tensile Properties of Single Textile Fiber, ASTM D3822," 2014.

[35] K. M. Rao and K. M. M. Rao, "Extraction and tensile properties of natural fibers: Vakka, date and bamboo," *Composite Structures,* vol. 77, no. 3, pp. 288-295, 2007.

[36] American society for testing and materials, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C39," 2016.

[37] D. Asprone, M. Durante, A. Prota and G. Manfredi, "Potential of structural pozzolanic matrix–hemp fiber grid composites," *Construction and Building Materials,* vol. 25, no. 6, p. 2867-2874, 2011.

[38] M. A. Sadek, L. Guzman, Y. Chen, C. Laguë and H. Landry, "Simulation of tensile tests of hemp fibre using discrete element method," *Agricultural Engineering International: CIGR Journal,* vol. 16, no. 2, pp. 126-135, 2014.

[39] K. Pickering, G. Beckermann, S. Alam and N. Foreman, "Optimising industrial hemp fibre for composites," *Composites Part A: Applied Science and Manufacturing,* vol. 38, no. 2, pp. 461-468, 2007.

[40] F. d. A. Silva, N. Chawla and R. D. d. T. Filho, "Tensile behavior of high performance natural (sisal) fibers," *Composites Science and Technology,* vol. 68, no. 15, pp. 3438-3443, 2008.

[41] P. R. Hornsby, E. Hinrichsen and K. Tarverdi, "Preparation and properties of polypropylene composites reinforced with wheat and flax straw fibres: Part I fibre characterization," *Journal of Materials Science,* vol. 32, no. 2, pp. 443-449, 1997.

[42] M. E. A. Fidelis, T. V. C. Pereira, O. d. F. M. Gomes, F. Silva and R. D. Toledo, "The effect of fiber morphology on the tensile strength of natural fibers.," *Journal of Materials Research and Technology,* vol. 2, no. 2, pp. 149-157, April-June 2013.

[43] V. Placet, "Characterization of the thermo-mechanical behaviour of hemp fibres intended for the manufacturing of high performance composites," *Composites Part A,* vol. 40, no. 8, pp. 1111-1118, 2009.

[44] K. Charlet, J. Jernot, J. Breard and M. Gomina, "Scattering of morphological and mechanical properties of flax fibres," *Industrial Crops & Products,* vol. 32, no. 3, pp. 220-224, 2010.

[45] R. El-Hacha, M. F. Green and G. Wight, "Effect of severe environmental exposures on CFRP wrapped concrete columns," *Journal of Composites for Construction,* vol. 14, no. 1, pp. 83-93, 2010.

[46] G. Wu, Z. Wu and Z. T. Lü, "Strength and ductility of concrete cylinders confined with FRP composites," *Construction and Building Materials,* vol. 20, no. 3, p. 134-148, 2006.

[47] H. M. Mohamed and R. Masmoudi, "Effect of test parameters on flexural strength of circular fiber-reinforced polymer-confined concrete beams," *Journal of Reinforced Plastics and Compositess,* vol. 31, no. 13, p. 897–914, 2012.

[48] P. Balaguru and H. Toutanji, "Durability characteristics of concrete columns wrapped with FRP tow sheets," *Journal of Materials in Civil Engineering,* vol. 10, no. 1, pp. 52-57, February 1998.

[49] A. Komuraiah, N. S. Kumar and B. D. Prasad, "Chemical Composition of Natural Fibers and its Influence on their Mechanical Properties," *Mechanics of Composite Materials*, vol. 50, no. 3, pp. 359-376, 2014.

[50] Z. Leman, S. M. Sapuan, M. Azwan, M. M. H. M. Ahmad and M. A. Maleque, "The effect of environmental treatments on fiber surface properties and tensile strength of sugar palm fiber-reinforced epoxy composites," *Polymer-Plastics Technology and Engineering,* vol. 47, no. 6, pp. 606-612, 2008.

[51] M. Ishak, Z. Leman, S. Sapuan, M. Salleh and S. Misri, "The effect of sea water treatment on the impact and flexural strength of sugar palm fibre reinforced epoxy composites," *International Journal of Mechanical and Materials Engineering (IJMME),* vol. 4, no. 3, pp. 316-320, 2009.

[52] A. Célino, S. Fréour, F. Jacquemin and P. Casari, "The hygroscopic behavior of plant fibers: a review," *Frontiers in Chemistry,* vol. 1, 2014.

[53] B. Wei, H. Cao and S. Song, "Environmental resistance and mechanical performance of basalt and glass fibers," *Materials Science & Engineering A*, vol. 527, no. 18, pp. 4708-4715, 2010.

[54] P. V. Joseph, K. Joseph, M. S. Rabello, L. H. C. Mattoso and S. Thomas, "Environmental effects on the degradation behaviour of sisal fibre reinforced polypropylene composites," *Composites Science and Technology,* vol. 62, no. 10, pp. 1357-1372, 2002.

[55] H. J. Kim and D. W. Seo, "Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites," *International Journal of Fatigue,* vol. 28, no. 10, pp. 1307-1314, 2006.