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PERFORMANCE OF A HYBRID CONCRETE STRUCTURE WITH NATURAL FIBRE REINFORCEMENTS

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Abstract

The use of natural fibres as reinforcement of concrete will be a significant step to have a sustainable construction industry. In this study, a hybrid concrete structure reinforced with natural fibre and natural fibre reinforced polymer composite was introduced, namely, flax fabric reinforced polymer composite (FFRP) tube encased coir fibre reinforced concrete (CFRC), termed as FFRP-CFRC. The compressive and flexural performance of this natural FFRP-CFRC structure were investigated under axial compression and four-point bending. In addition, the effect of ultraviolet radiation and water spray ageing (1500 h exposure) on the mechanical properties of FFRP composites was investigated to study the durability of FFRP composites for civil engineering application. The test results indicate that in axial compression, the use of natural FFRP tube increased the compressive strength and ductility of concrete remarkably. In flexure, the FFRP tube enhanced the lateral load carrying capacity concrete significantly. Coir fiber inclusion changed the failure mode of concrete to be ductile. The ageing conditions cause severe degradation in the tensile and flexural properties of FFRP composites, which was induced by the degradation in flax fibre and polymer matrix interfacial bonding. Overall, this study shows that the hybrid structure has the potential to be light and environmentally-friendly structure for infrastructure application. However, how to improve the durability of FFRP composites is a critical issue which should be considered in the future study.

Keywords:

Natural fibres; Fibre reinforced polymer composites, Fibre reinforced concrete

1 INTRODUCTION

Construction and building industries are the two major and most active sectors in the world. In Europe, they represent 28.1% and 7.5% of employment in industry and in the European economy, respectively [1]. They also account for the consumption of large amounts of non-renewable resources, 40% of energy consumption and greenhouse gas emission (e.g. CO_2) which cause environmental issues, such as climate warning and air pollution [2]. The severe environmental issues requires the development of sustainable concrete and structure industries urgently.

Recently, due to the increasing environmental concerns, using fibres from natural resources (i.e. vegetable fibres) to substitute synthetic fibres (e.g carbon/glass) for fibre reinforced polymer (FRP) composite application has gained popularity [3-5]. Natural fibres, e.g. flax, hemp, jute, coir and sisal, are cost effective, have high specific strength and specific stiffness and are readily available [6,7]. Among various natural fibres, flax fibres with tensile properties are comparable to those of glass fibres. Flax offers the best potential combination of low cost, light weight, and high strength and stiffness for structural applications [8]. Other scholars also recommended composites reinforced with natural fibres for civil engineering applications (e.g. Dittenber and GangaRao [9]). Assarar et al. [10] found that the tensile strength of flax/epoxy composite was 300 MPa, closing to glass/epoxy composite. So, it is feasible to replace synthetic FRP composites by the more economical bio-composites for civil engineering applications. For instance, synthetic glass or carbon FRP composite tubes have been used in a new structural system (i.e. FRP tube confined concrete) to enhance concrete strength and ductility because of the confinement effect provided by the FRP tubes.

Studies on fibre reinforced concrete indicated that short natural fibres can modify tensile and flexural strength, toughness, impact resistance and fracture energy when used within cementitious [11]. Pacheco-Torgal and Jalali [1] concluded that vegetable fibres (e.g. sisal, hemp, coir, banana and sugar cane bagasse, etc) can be used as reinforcement for cementitious materials. Coir fibre, because of its highest toughness among natural fibres and the extremely low cost and availability, is good fibre reinforcement for concrete structures [12]. It is reported that coir fibre bridging effect increased the flexural toughness of cementitious composites by more than 10 times [13]. The effectiveness of coir fibre on the flexural properties (e.g. flexural toughness) of cementitious composites was even better than synthetic glass or carbon fibres. Hasan et al. [14] suggested that coir fibres can be used as reinforcement for lightweight concrete structures. Therefore, natural fibre reinforced polymer composites can be used to replace conventional steel reinforcement of concrete structures and natural fibres within cementitious can also be considered as reinforcement of concrete. The use of concrete and concrete structures with natural fibres will make the construction industry more sustainable.

On the basis of this, the author developed a new steel-free concrete composite structure with natural fibre reinforcements, namely, natural flax fibre reinforced polymer (FFRP) tube encased coir fibre reinforced concrete (CFRC), which is termed as FFRP-CFRC. This new composite structure is composed of an outer FFRP tube and a CFRC core, as shown in Fig. 1. This pre-fabricated FFRP tube made of flax fabric reinforced epoxy composites acts as permanent formworks for fresh concrete and also provides confinement to concrete. Coir fibre is the reinforcement of the concrete core to reduce the crack width and in turn modifies the failure mode of composite structure to be ductile as a result of fibre bridging effect. Therefore, one purpose of this study is to exhibit the compressive and flexural performance of this hybrid concrete structure. In addition, the lack of data related to durability is one major challenge that needed to be addressed prior to the widespread acceptance of natural fibre reinforced polymer composites for civil engineering applications. Thus, another purpose of this study is to investigate the effect of ultraviolet (UV) radiation and water spraying on the mechanical properties of flax fabric reinforced epoxy composite to assess the durability performance of this composite.

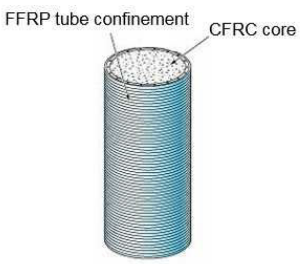

Fig. 1: Schematic view of a FFRP-CFRC.

2 EXPERIMENTAL PROCEDURE

2.1 Materials and Fabrication

Commercial bidirectional woven flax fabric was used for the study. The Epoxy was SP High Modulus LV 20 resin and hardener. The fabric has a plain woven structure with count of 7.4 threads/cm in warp and 7.4 threads/cm in the weft direction. FFRP tubes were fabricated using a hand lay-up process. The thickness of the FFRP tubes with 4 layers of fabric. For fabrication of FFRP tubes, an aluminium mould was first cut longitudinally, and then taped tightly to make a formwork for FRP wrapping, while allowing easy removal of the tube after the curing of FFRP. Then the aluminium mould was covered with a layer of infusion sheet, so that the cured FFRP tubes can be easily detached. Fabric fibre orientation was at 90^{o} from the axial direction of the tube. The tensile strength and modulus of the FFRP composite laminate is 134 MPa and 9.5 GPa and the flexural strength and modulus of the composite laminate is 144 MPa and 8.7 GPa, respectively. For FFRP laminate specimens used for durability investigation, the panel was also fabricated with the hand lay-up process. The thickness of the FFRP laminates is also 4 layers of flax fabric.

2.2 Concrete specimens

Two types of concrete were prepared, plain concrete (PC) and coir fibre reinforced concrete (CFRC). Type I Portland cement, gravel, natural sand and water were used to prepare concrete. Concrete with 28-day compressive strength of 30 MPa was designed. The mix ratio by weight was 1:0.55:3.82:2.27 for cement: water: gravel: sand, respectively [15]. For CFRC, coir fibres were added during the mixing. The fibre length was 50 mm with fibre content of 1% of cement by mass. For each FFRP tube confined concrete specimen, one end of the tube was capped with a wooden plate before concrete pouring. Then concrete was cast, poured, compacted and cured in a standard curing water tank for 28 days. Both end sides of the specimens were treated with plaster to have a uniform bearing surface and a blade was used to cut the upper and lower edges of tube–confined specimen to avoid it directly from bearing the axial compression [15].

2.3 Testing

For axial compression test, two strain gauges were attached at the mid-height of the cylindrical specimen in the hoop direction to monitor lateral strains. Two linear variable displacement transducers (LVDTs) were attached 180^{o} apart and covered and spaced 130 mm centred at the mid-height to measure axial strain (Fig. 2(a)) [15]. Compression test was conducted on an Avery-Denison machine under stress control with a constant rate of 0.20 MPa/s based on ASTM C39. Each sample was axially compressed up to failure. Readings of the strain gauges and LVDTs were taken using a data logging system. For four-point bending test, three strain gauges were mounted at the mid-span of each long cylindrical specimen aligned along the hoop direction to monitor the lateral strain and another three strain gauges at the axial direction of tube to measure the axial strain (Fig. 2(b)). One LVDT was covered the lower boundary of the composite column at the mid-span to measure the deflection of the column. The four-point bending test was conducted on Instron testing machine according to ASTM C78 standard.

Fig. 2: Axial compression (a) and four point bending (b) test.

For durability investigation of FFRP composites, the FFRP laminate specimens were exposed to Fluorescent UV light in an accelerated weathering chamber according to ASTM D4329. A single exposure cycle included four steps: (1) 12 h of UV light exposure at 60°C, (2) place at room temperature for 3 h, (3) spraying water to the exposed surface and exposed to UV light for 6 h at 60°C, and (4) place at room temperature for 3 h before the next cycle. The total exposure time was 1500 h. The tensile and flexural test of FFRP composite flat-coupon laminates was performed in accordance with ASTM D3039 and ASTM D790, respectively. Fig. 3 and Fig. 4 shows the tensile test and flexural of FFRP laminate, respectively.

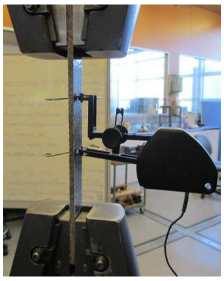

Fig. 3: Tensile test of flat-coupon FFRP laminate.

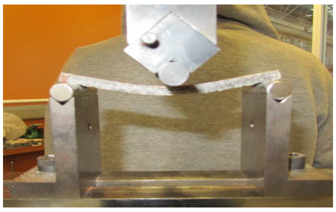

Fig. 4: Flexural test of flat-coupon FFRP laminate.

3 RESULTS AND DISCUSSION

3.1 Compressive behaviour

The axial compressive stress and axial strain curves of the PC and FFRP-PC (FFRP tube confined plain concrete), CFRC and FFRP-CFRC are displayed in Fig. 5 and Fig. 6, respectively. It can be seen that the stress-strain response of FFRP confined concrete is significantly influenced by the FFRP confinement. The axial stress-strain responses of both FFRP-PC and FFRP-CFRC specimens show a distinct bi-linear manner. When the applied axial stress is low, the stress-strain response of FFRP-PC or FFRP-CFRC is similar to the unconfined PC or CFRC. When the applied stress approaches the peak strength of the unconfined PC or CFRC, the curve enters a short nonlinear transition region where considerable micro-cracks are propagated and the lateral expansion significantly increased in the concrete. The second linear curve of FFRP-PC or FFRP-CFRC displays an ascending branch, indicating the good confinement of the FFRP tube. The linear response in this region is mainly dominated by the structural behaviour of FFRP composites [16,17].

For FRP tube confined concrete, the confinement effectiveness is defined as the ratio of the peak compressive strength of confined concrete to the peak strength of unconfined concrete. The axial strain ratio is the ratio of ultimate axial strain to that of the unconfined concrete at peak strength, which is used to define the ductility of the concrete. The test results in Fig. 5 and Fig. 6 show that the compressive strength of PC and CFRC is 25.8 MPa and 28.2 MPa and the ultimate axial strain at the peak strength is 0.20% and 0.54%, respectively. It shows that the addition of coir fibre increases the compressive strength and the axial strain because of the fibre bridging effect. The ultimate compressive strength of FFRP-PC and FFRP-CFRC is 53.7 MPa and 56.2 MPa, respectively, corresponding to the confinement effectiveness of 2.08 and 2.0 for FFRP-PC and FFRP-CFRC with tube thickness of 4 layer flax fabric. The data here indicates that the FFRP tube confinement increases the load carrying capacity of PC and CFRC up to 108% and 100%, respectively. The ultimate axial strain of FFRP-PC and FFRP-CFRC is 2.25% and 2.70%, respectively. So, compared with the ultimate axial strain of PC, the axial strain ratio for FFRP-PC and FFRP-CFRC is 11.3 and 13.5, respectively, indicating that the FFRP tube confinement increases the ductility of PC and CFRC remarkably. Therefore, the FFRP tube confinement increases the load carrying capacity and ductility of concrete significantly.

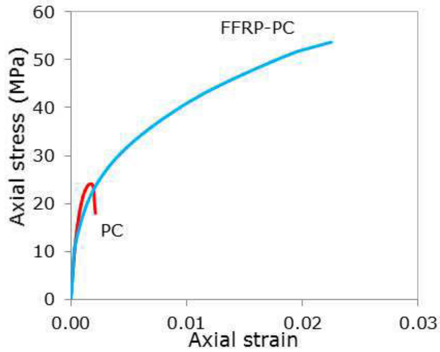

Fig. 5: Axial compressive stress-strain behaviour of PC and FFRP-PC.

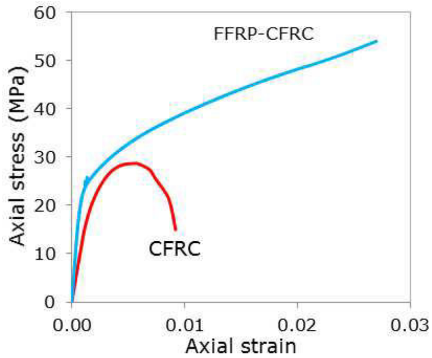

Fig. 6: Axial compressive stress-strain behaviour of CFRC and FFRP-CFRC.

3.2 Flexural behaviour

The load versus mid-span deflection responses of PC and FFRP-PC, and CFRC and FFRP-CFRC under bending test are displayed in Fig. 7 and Fig. 8, respectively. PC specimen exhibited a linear response up to failure showing a pure brittle failure of the unreinforced concrete. The curve was very short indicating the negligible load carrying capacity and deflection of the specimen. For CFRC, the curve also shows a linear response up to the peak load but it followed with a post-softening response, indicating a ductile behaviour of the specimen. It is believed that the coir fiber inclusion is responsible for this post-peak response. For FFRP tube confined concrete specimens, it can be seen that the response of the confined concrete specimen is dominated by the strength and stiffness of the FFRP tube. Both the FFRP tube confined PC and CFRC specimens possessed a nonlinear load-deflection response before approaching the peak load. Like that of unconfined PC, the FFRP-PC specimen also exhibited a brittle failure as the result of the non-yielding characteristics of FFRP materials. However, on the other hand, the

FFRP-CFRC specimen had a post-softening curve with a ductile response, showing the advantageous of coir fibers. It is believed that this post-peak ductile response of FFRP-CFRC specimen is attributed to the fiber bridge effect, which will be discussed in the following failure mode section. For the confined PC and CFRC, it is clear that there were some sudden load drops in the load-deflection curves, which can be explained by the occurrence of the slippage between the concrete core and the FFRP tube. Slippage between the concrete core and the FFRP tube may compromise the ultimate load carrying capacity of the FFRP and concrete composite column. Therefore, special arrangement should be considered to roughen the inner surface of the FFRP tubes to prevent slippage and may further increase the load carrying capacity of the composite column.

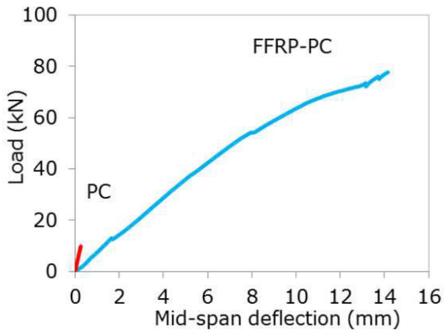

Fig. 7: Load and displacement of PC and FFRP-PC.

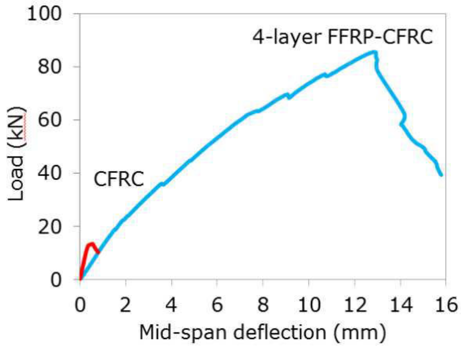

Fig. 8: Load and displacement of CFRC and FFRP-CFRC.

Since no reinforcement was used in the unconfined PC specimen, the ability to carry the lateral load was negligible, with a load of 7.4 kN. For CFRC specimen, the coir fiber inclusion increased the peak load to 10.1 kN, with an increase of 36.5%. In the case of FFRP tube confined concrete, the FFRP tube confinement enhanced the load carrying capacity significantly, with the increase is 1066% and 946% for the confined PC and CFRC, compared to the corresponding unconfined PC and CFRC, respectively. Additionally, the coir fiber inclusion slightly increased the peak load of FFRP-CFRC (84.7 kN) compared to the FFRP-PC (78.9 kN). Therefore, coir fiber inclusion led to better flexural properties.

3.3 Durability of FFRP composites

Fig. 9 shows the surface of the FFRP composite before and after UV weathering. It is clear that the composite had severe discoloration after UV weathering. The weathered specimen surface and edges experienced degradation such as erosion of polymer matrix and formation of voids, which are the signs of surface degradation after exposure [19]. It is believed the discolouration of the composite attributable to the degradation of the epoxy matrix and the fibres after the long-time UV radiation and water spraying cycles. UV radiation exposure generated a thin surface layer of chemically modified epoxy. Subsequent water spraying and condensation leached away soluble degradation stuff, which exposed a fresh layer that can be attacked by UV radiation once again. Thus, the repetitive process resulted in significant erosion of the epoxy matrix. In addition, the absorbed water molecules in the epoxy matrix also accelerated the photo-oxidation reactions because of the availability of OH^- and H^+ ions during the weathering cycles [18]. The severe erosion of epoxy matrix due to UV radiation and water spraying could cause loss of structural integrity in composite structures [18,19].

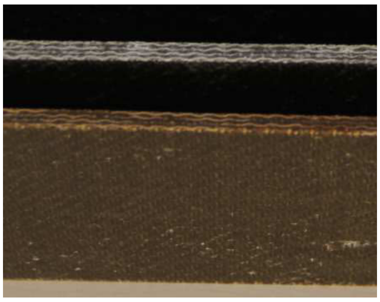

Fig. 9: General observation of controlled (upper) and 1500 h UV exposure (lower) FFRP composites

The tensile properties of the controlled and weathered FFRP composites (exposure to 1500 h) are illustrated in Fig. 10. The results show that compared to the pure epoxy, the tensile properties of the controlled composite increased remarkably. The increase in tensile strength and modulus for the controlled composite is 61.4% and 132.4%, respectively. Fig. 10 also indicates that the tensile strength and modulus at break of the FFRP composite all reduced after 1500 h of UV radiation and water spraying cycle. Compared with the controlled specimen, the tensile strength of weathered one decreased from 116.2 MPa to 81.5 MPa, with a reduction of 29.9%. For the tensile modulus, the reduction after exposure is 34.9% (from 8.6 to 5.6 GPa).

The flexural properties of controlled (without weathering) and weathered flax fabric/epoxy composites (exposure to 1500 h) are displayed in Fig 11. Compared to the epoxy resin, the flexural strength and modulus of the controlled composite increased 66.2% and 117.9%, respectively [19]. As illustrated in Fig. 11, the weathering also has a negative effect on the flexural strength and modulus of the composite. Compared to the controlled composite, the reduction in the flexural strength and modulus of the weathered composite is 10.0% and 10.2%, respectively [19].

The degradation of the composite tensile/flexural properties was mainly attributed to the degradation of the flax fibres and the fibre/matrix interfacial bonding. In the accelerated weathering chamber, the UV light and the high humidity (water spraying) cycles had negative effect on the contents of the cellulose, hemicellulose, and lignin within the flax fibre. For flax fibre, the main constituents are cellulose, hemicellulose, wax, lignin and pectin, in varying quantities. Cellulose is the stiffest and the strongest organic constituent in the fibre which determines the tensile properties of the fibre thus those of the composite [8]. The celluloses are embedded in hemicellulose and lignin matrices in the flax fibre. Hemicellulose with open structure containing many hydroxyl and acetyl groups, which is responsible for the moisture absorption thus the thermal degradation of flax fibre. Lignins are amorphous, highly complex, mainly aromatic, polymers which responsible for the ultraviolet degradation [8]. The breaking down of cellulose, hemicellulose and lignin after exposure could lead to poor interfacial bond between the epoxy matrix and the flax fibres. In addition, the weathering cycles tend to increase the wettability of the flax fibres by removing the hydrophobic substances such as hydrocarbons, waxes and lignin [18], which also contributed to the degradation of fibre/matrix interfacial bond, since lignin and waxes act mainly as bonding agents in flax fibres. Thus, the poor fibre/matrix interfacial bond in turn caused a lower tensile/flexural properties of the composites because the load transfer from fibre to fibre is through the fibre/matrix interface [19].

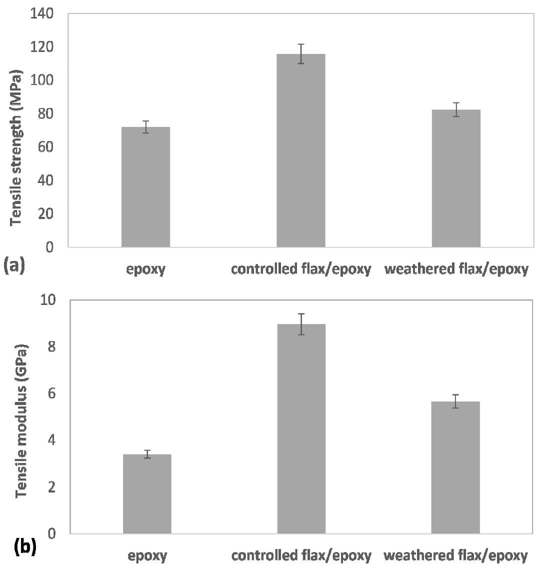

Fig. 10: Tensile strength (a) and modulus (b) of control and weathered FFRP composites

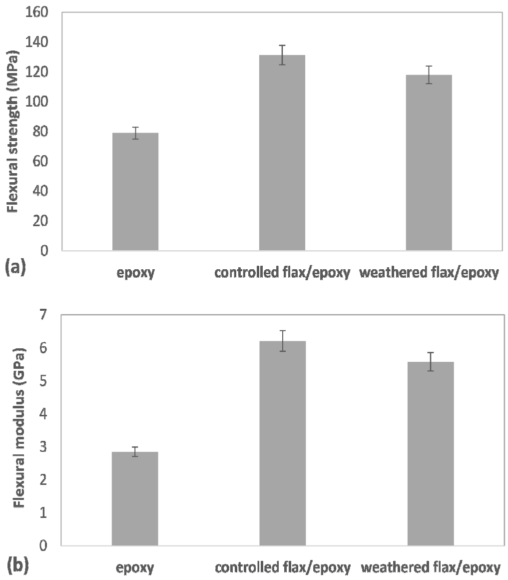

Fig. 11: Flexural strength (a) and modulus (b) of control and weathered FFRP composites.

The scanning electron microscope (SEM) images of fractured surfaces of the controlled and weathered flax fibres are shown in Fig. 12. The weathered flax fibre had a major crack at the tip of the fibre, which is believed attributable to the wetting/drying cycles and the UV radiation. The weathering caused damage to the flax fibre hence degraded the mechanical properties of the fibre [19]. In addition, the comparison between Fig 12(a) and (b) shows less surface impurities such as residual epoxy matrix on the weathered fibre surroundings, indicating the poor fibre/matrix interfacial bonding during the tensile failure for the weathered fibres. In the weathering chamber, the cycles of UV radiation and high moisture alternated, the flax fabric/epoxy composite continually suffered from adsorption/desorption cycles, leading severe shrinkage of the epoxy matrix and in turn the degradation at fibre/matrix interfaces. Consequently, the degradation of the fibre/matrix interfacial bond caused the lower mechanical properties of the composites [19].

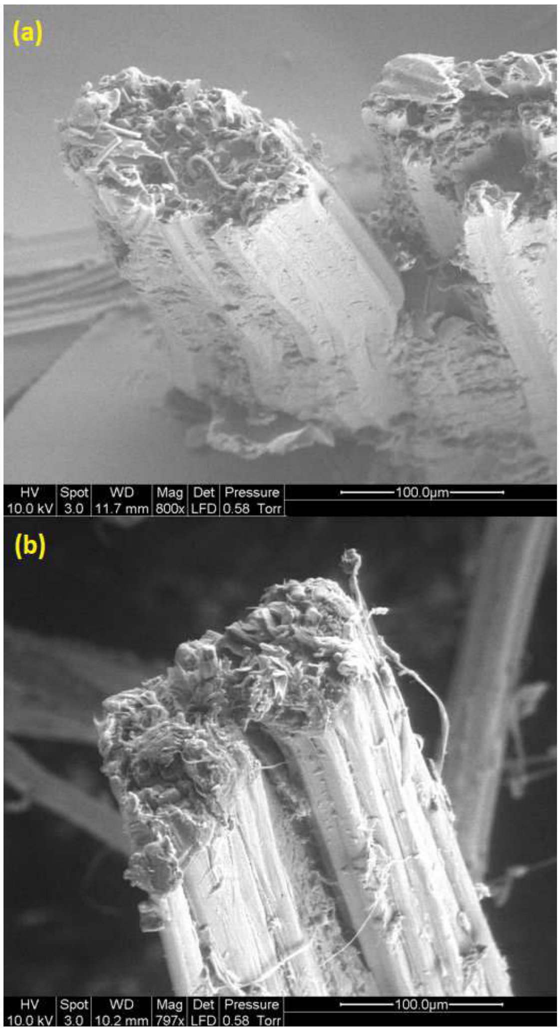

Fig. 12: SEM image of surfaces for the controlled (a) and weathered (b) flax fibres.

4 SUMMARY

In this study, the compressive and flexural properties of flax fabric reinforced polymer (FFRP) tube confined coir fiber reinforced concrete (CFRC) were experimentally investigated. In addition, the effect of UV ageing on the mechanical properties of FFRP composites was investigated to study the durability of the FFRP for civil engineering application. This study reveals: in compression, FFRP tube confinement enhanced the compressive strength and ductility of both PC and CFRC cylinders significantly. In flexure, FFRP tube confinement increases the ultimate lateral load and mid-span deflection of the PC and CFRC members remarkably. FFRP-PC columns exhibit a brittle failure mode while FFRP-CFRC columns behave a ductile manner due to coir fibre bridging effect. Durability study shows that the UV weathering results in degradation for the tensile and flexural properties of FFRP composites. The tensile strength/modulus of the weathered composites decreased 29.9% and 34.9%, respectively. The flexural strength/modulus reduced 10.0% and 10.2%, respectively. SEM study confirmed the degradation in fibre/matrix interfacial bonding after exposure. In general, flax FRP tube confined coir fibre reinforced concrete columns have the potential to be compressive and flexural structural members. The use of coir and flax fibres as construction materials will be benefit to build a construction industry with more environmentally-friendly and lower carbon footprint. However, proper treatments to enhance the durability performance of natural flax fibre reinforced polymer composite will make it more promising as construction building material.

5 REFERENCES

[1] Pacheco-Torgal F, Jalali S. Cementitious building materials reinforced with vegetable fibres: A review. Construction and Building Materials 2011;25:575-581.

[2] Yan LB, Chouw N. Experimental study of flax FRP tube encased coir fibre reinforced concrete composite column. Construction and Building Materials 2013;401118-1127.

[3] Yan LB, Chouw N. Crashworthiness characteristics of flax fibre reinforced epoxy tubes for energy absorption application. Materials & Design 2013;51: 629-640.

[4] Yan LB, Chouw N, Jayaraman K. Lateral crushing of empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes. Composites Part B 2014;63:15-26.

[5] Yan LB, Chouw N, Jayaraman K. Effect of triggering and polyurethane foam-filler on axial crushing of natural flax/epoxy composite tubes. Materials & Design 2014;56:528-541.

[6] Yan LB. Effect of alkali treatment on vibration characteristics and mechanical properties of natural fabric reinforced composites. Journal of Reinforced Plastics and Composites 2013;31(13):887-896.

[7] Yan LB, Chouw N, Yuan XW. Improving the mechanical properties of natural fibre fabric reinforced epoxy composites by alkali treatment. Journal of Reinforced Plastics and Composites 2012;36(6):435-437.

[8] Yan LB, Chouw N, Jayaraman K. Flax fibre and its composites: A review. Composites Part B: Engineering 2014;56:296-317.

[9] Dittenber DB, GangaRao HVS. Critical review of recent publications on use of natural composites in infrastructure. Composites Part A 2012; 43(8):1419-1429.

[10] Assarar M, Scida D, El Mahi A, Poilâne C, et al. Influence of water ageing on mechanical properties and damage events of two reinforced composite materials: Flax–fibres and glass–fibres. Materials & Design 2011;32(2):788-795.

[11] Yan LB, Chouw N. Dynamic and static properties of flax fibre reinforced polymer tube confined coir fibre reinforced concrete. Journal of Composite Materials 2014;48(13):1595-1610.

[12] Li Z, Wang L, Wang X. Flexural characteristics of coir fibre reinforced cementitious composites. Fibers and Polymers 2006;7(3):286–294.

[13] Reis J. Fracture and flexural characterization of natural fibre-reinforced polymer concrete. Construction and Building Materials 2006;20(9):673–678.

[14] Hasan NMS, Sobuz HR, Sayed MS, Islam SM. The use of coconut fibre in the production of structural lightweight concrete. J Applied Sciences 2012;12(9): 831-839.

[15] Yan L, Chouw N. Natural FRP tube confined fibre reinforced concrete under pure axial compression. Thin-Walled Structures 2014;82:159-169.

[16] Yan L, Chouw N. A comparative study of steel reinforced concrete and flax fibre reinforced polymer tube confined coconut fibre reinforced concrete beams. Journal of Reinforced Plastics and Composites 2013;32(16):1-10.

[17] Yan L, Chouw N, Jayaraman K. Effect of column parameters on flax FRP confined coir fibre reinforced concrete. Construction and Building Materials 2014;55:299-312.

[18] Kumar BG, Singh RP, Nakamura T. Degradation of carbon fibre-reinforced epoxy composites by ultraviolet radiation and condensation. Journal Composite Materials 2002;36(24):2713-2733.

[19] Yan LB, Chouw N, Jayaraman K. Effect of UV and water spraying on the mechanical properties of flax fabric reinforced polymer composites used for civil engineering application. Materials & Design 2014;56:528-541.