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Effect of water, seawater and alkaline solution ageing on mechanical properties of flax fabric/epoxy composites used for civil engineering applications

Libo Yan [a,b,*], Nawawi Chouw [c]

[a] Department of Organic and Wood-Based Construction Materials, Technical University of Braunschweig, Hopfengarten 20, 38102 Braunschweig, Germany
[b] Centre for Light and Environmentally-Friendly Structures, Fraunhofer Wilhelm-Klauditz-Institut WKI, Bienroder Weg 54E, 38108 Braunschweig, Germany
[c] Department of Civil and Environmental Engineering, The University of Auckland, Auckland Mail Centre, Private Bag 92019, Auckland 1142, New Zealand

HIGHLIGHTS

- Flax-epoxy composites are used as external strengthening of concrete.
- Ageing conditions degraded mechanical properties of flax/epoxy composites.
- SEM confirmed degradation in fibre/matrix interfacial bonding.
- Ageing conditions caused discolouration and microcracking.

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ABSTRACT

Durability performance is one critical concern regarding the acceptance of bio-composites for civil engineering application. In this study, the effects of water, seawater and alkaline (5% NaOH) solution ageing conditions on flax fabric reinforced epoxy composites used for civil engineering applications (i.e. as external strengthening and confinement of concrete) were investigated. Composite laminate specimens manufactured by hand lay-up were immersed in those ageing solutions for 365 days. Tensile and three-point bending tests were performed to examine the mechanical properties of the composites. Scanning electron microscope (SEM) was used to analysis the microstructures of the composites. The results show that all the aged composites had high weight gain (8.5–9.4%) after the long-term immersion. All the ageing solutions resulted in remarkable degradation in tensile/flexural properties of the composites. The reduction in tensile strength and modulus was 22.6–31.1% and 24.0–36.4% and the reduction in flexural strength and modulus was 9.3–23.5% and 13.9–25.2%, respectively. Alkaline ageing led to the largest reduction, followed by seawater and then the water ageing. The reduction in mechanical properties induced by degradation for fibre/polymer interfacial bonding was confirmed by SEM images. Comparisons with synthetic fibre reinforced polymer composites indicate that both natural (i.e. flax) and synthetic (i.e. glass and carbon) fibre composites experienced severe degradation after ageing in water, seawater and alkaline solution. Flax/epoxy composites could be comparable to synthetic composites in the aspects of durability performance for civil engineering application.

1. Introduction

In the past decade, using natural fibres to replace synthetic fibres (e.g. glass) as composite reinforcement materials has gain popularity due to the increasing environmental concern and the high demand for environmentally-friendly materials [1]. The main impetus of using natural fibres is their ecological benefits: natural fibres are non-abrasive, less energy consumption and health risk, recyclable and bio-degradable, which being regarded as the representative of highly "sustainable" materials [2]. Composites reinforced with natural fibres offer potential to create large-volume, biodegradable structural components using only renewable resources, resulting in reduced quantities of embodied energy [3]. One of the most important and promising area for future application of natural fibre reinforced composites is probably in civil

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* Corresponding author at: Department of Organic and Wood-Based Construction Materials, Technical University of Braunschweig, Hopfengarten 20, 38102 Braunschweig, Germany.

E-mail addresses: l.yan@tu-braunschweig.de, libo.yan@wki.fraunhofer.de (L. Yan).

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engineering as construction and building materials. Natural fibre reinforced composites have the potential to eventually be lighter-weight and lower cost than synthetic fibre reinforced composites [4]. Natural fibre composites also have good thermal and acoustic insulation properties. Using materials like natural fibre composites would provide long term benefits to infrastructure. It will reduce construction waste and increase energy efficiency which provide a solution to immediate infrastructure needs while promoting the concept of sustainability [5].

Among various natural fibres, flax is regarded as a suitable candidate to replace glass as composite reinforcement material. Dittenber and GangaRao [6] compared more than 20 commonly used natural fibres with glass fibre in specific Young's modulus, cost per weight and cost per unit length to resist load. They concluded that flax offers the best potential combination of low cost, light weight, and high strength/stiffness for structural applications. Yan et al. [4] found that flax, hemp and jute are the three most promising candidates for replacing glass for composites when taking cost, mechanical performance and production yielding into account. Assarar et al. [7] compared the mechanical properties of flax fabric/epoxy composite with those of glass/epoxy composites. The tensile strength of the flax/epoxy composite was 380 MPa, which was close to glass/epoxy composite. Di Bella et al. [41,42] studied natural fibre reinforced polymer composites for different engineering applications. They compared the mechanical properties of flax fabric reinforced composites with glass fabric fibre reinforced composites. Their studies shown that the flax fabric reinforced composites can be used in several fields, such as marine or automotive. Shah et al. [8] performed a comparative study between flax and glass fibre reinforced composites and found that flax fibre is a suitable structural replacement to E-glass for composite wind turbine blade applications. In addition, Yan et al. [9–12] and Meredith et al. [13] even considered flax fibre reinforced composites as crashworthy structures (e.g. energy absorber devices) for vehicle design. These studies showed that flax fibre reinforced composites exhibited good crashworthiness characteristics and energy absorption capability as those of conventional metallic structures (e.g. stainless steel and aluminum) or synthetic (e.g. glass and carbon) fibre composite structures, thus, had the potential to be new energy absorber device for automotive engineering application.

For civil engineering application, Le Duigou et al. [14,15] studied the feasibility of flax fibre reinforced composite sandwich used for transport application. Cevallos and Olivito [16,17] tested the mechanical properties of flax fabric fibre reinforced cementitious composites and showed that the flax fabric reinforced composites exhibited ductile behavior and were suitable for strengthening applications in masonry structures. Yan et al. [18–23] conducted a series of studies on the structural performance of a hybrid structure consisting of an outer flax fibre reinforced composite tube and a coir fibre reinforced concrete core, i.e. flax fibre reinforced polymer (FFRP) tube encased coir fibre reinforced concrete (CFRC) structure (termed as FFRP–CFRC). In this FFRP–CFRC system, the pre-fabricated flax fabric/epoxy composite tube serves as permanent formwork for fresh concrete and provides confinement to concrete to increase its strength and ductility. Coir fibres as reinforcement within concrete are used to reduce concrete cracks. Fig. 1 shows the FFRP–CFRC hybrid structure. Previous studies [18–20] showed a good potential of FFRP–CFRC structure as axial and flexural structural members. In addition, in vibration, flax fabric reinforced composite tube and coir fibre increased the damping characteristics of the hybrid structure, thus reduced the effect of dynamic loadings on the structural response, showing the potential as earthquake-resistant structure [21]. FFRP–CFRC structure also showed better structural performance (i.e. energy dissipation and load carrying capabilities) than conventional steel reinforced concrete [22]. Compared with the confinement effectiveness of synthetic (i.e. glass, carbon or aramid) fibre reinforced polymer composite tube on concrete columns, the confinement performance of natural flax/fabric reinforced polymer composite tube on concrete columns is comparable [23]. Studies [14–23] above showed the good structural performance of natural flax fibre reinforced composites for infrastructure application.

However, durability performance is one critical issue which should be considered for practical engineering applications of natural (i.e. flax) fibre reinforced composites. The lack of data related to durability is a major challenge that needed to be addressed prior to the widespread acceptance of natural fibre reinforced composites for practical engineering application [4,24,25]. For example, FFRP–CFRC hybrid structure, if being used in practice, the flax reinforced composites will be exposed to a range of aggressive environments (e.g. humidity, basic, acid and alkaline solutions, temperature, freeze-thaw, thermal cycles, UV rays, etc.) during their in-service life, which can cause degradation of composite mechanical properties and thus raise safety concerns. Therefore, understanding the durability performance of flax fibre reinforced composites has potential industrial significance. To date, in the literature, studies on durability investigation of flax fabric reinforced polymer composites subjected to long term water, seawater (marine environment) and alkaline solutions (a simulation of concrete pore water) are very rare. Therefore, the aim of this work is study the effects of those ageing conditions on the mechanical properties of flax fabric/epoxy composites.

2. Materials and experimental procedure

Bidirectional woven flax fabric (550 g/m^2) was used because initially it was used to make flax fabric/epoxy composite tubes for FFRP–CFRC hybrid structure. The structures of flax fabric and single-strand flax yarn extracted from the fabric are displayed in Fig. 2. The epoxy used was SP High Modulus Prime 20 resin and its hardener. The physical and mechanical properties of flax fibre yarn and epoxy are listed in Table 1 [11]. In previous studies [19–21], these flax fabric/epoxy tubes for FFRP–CFRC hybrid structures were fabricated using hand layup process. In order to keep the same situation, the hand lay-up process was also used in this study.

The composite laminate samples were immersed in water, fresh natural seawater (a salinity of about 3.5%) and 5% NaOH (sodium hydroxide) solution in sealed containers at laboratory conditions (20 °C) for 365 days. During the environmental ageing process, the samples were taken out every 2 month and weighed to analyse the weight change of the specimens. The absorption of the composites after different solutions immersion was determined by the weight gain relative to the oven dry weight according to ASTM D570. For the analysis of weight gain, three samples were weighed for each composite type. The absorption in weight percentage ($W\%$) was calculated from Eq. (1) below:

$$W(\%) = \frac{W_t - W_o}{W_t} \times 100 \tag{1}$$

where W_t and W_o denotes weight of wet composite at time t and the weight of dry specimen, respectively.

Tensile test was performed in accordance with ASTM D3039 using a cross-head speed of 2 mm/min at the room temperature. The size of the laminates was $250 \times 25 \times 5.3$ mm^3. During the testing, an extensometer with a gauge was placed to the specimen to record the elongation. Tensile results were obtained directly from the machine. Flexural test was performed in accordance with the ASTM D790 using a cross-head speed of 2.2 mm/min. The size of the laminates was $100 \times 20 \times 5.3$ mm^3. The length of the support span was 80 mm and the overhang length on both side was 10 mm. Flexural properties were obtained directly from the machine. For both tensile and flexural tests, five specimens were tested for each composite.

The surface and tensile fractured surfaces of the composites were analysed using an SEM (Philips XL30S FEG, Netherlands) at room temperature with an acceleration voltage of 10 kV. Prior to analysis, the sample surfaces were vacuum-coated by evaporation with platinum.

3. Results and discussion

3.1. Visual observations after immersion in different solutions

Fig. 3 shows the images of the flax fabric reinforced epoxy composites before (control) and after immersed in different ageing