Tensile properties of glass/natural jute fibre-reinforced polymer bars for concrete reinforcement

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Abstract. The tensile performance of glass/natural jute fibre-reinforced polymer (FRP) bar, intended for concrete reinforcement was evaluated as a function of volume fraction of natural jute fibre. Natural jute fibre, mixed at a ratio of 7:3 with vinyl ester, was surface-treated with a silane coupling agent and used to replaced glass fibre in the composite in volume fractions of 0%, 30%, 50%, 70%, and 100%. The tensile load–displacement curve showed nearly linear elastic behaviour up to 50% natural jute fibre, but was partially nonlinear at a proportion of 70%. However, the glass/natural jute FRP bars prepared using 100% natural jute fibre showed linear elastic behaviour. Tensile strength decreased as the natural jute fibre volume fraction increased because the tensile strength of natural jute fibre is much lower than that of glass fibre (about 1:8.65). The degree of reduction was not proportional to the natural jute fibre volume fraction due to the low density of natural jute fibre (1/2 that of glass fibre). Thus, as the mix proportion of natural jute fibre increased, the amount (wt%) and number of fibres used also increased.

1. Introduction
Environmental pollution and global warming concerns have prompted research and development of new biocomposite materials for various applications [1-4]. An example of this is the replacement of synthetic fibres made from petroleum products (e.g. polymers) with inexpensive, lightweight, naturally occurring fibres from plant and animal resources [5-10]. Natural fibres used in biocomposite materials, such as jute, flax, kenaf, and hemp, offers many advantages [4, 11]. Natural fibres are biodegradable, easier to recycle than synthetic fibre, and may be effective in reducing overall unit production cost by increasing the efficiency of production, thus reducing carbon emissions. Reinforcement bars, widely used in concrete structures to increase tensile strength are prone to corrosion [12-16]. To address this issue, research has been conducted on the tensile reinforcing properties of fibre-reinforced polymer (FRP) composites based on glass, carbon, and aramid fibres [17-21] FRP materials, applied to concrete in the form of bars, plates, and sheets, are resistant to corrosion and highly durable in the long term. Additionally, FRP reinforcing bars have a similar form

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to steel bars. The use of FRP as a reinforcement material has steadily increased, though it is more expensive than steel [12-21]. This study developed a tensile reinforcing bar made from biocomposite materials as a replacement for tensile reinforcing bars that use a glass fibre (GFRP) composite. To date, most of the research on concrete reinforcement has focused on the sheet/plate form of biofibre-based composite materials; few studies have investigated the bar form [3, 4, 22, 23]. In general, the price of biofibres is about 1/3 to 1/5 that of glass fibre [3, 4]. Despite the low cost, biofibre has a low density (1.2–1.5 g cm$^{-3}$) compared with that of glass fibre (2.56 g cm$^{-3}$), as well as lower strength and elasticity; however, the specific strength and specific elasticity modulus of natural fibre and glass fibre are comparable [3, 4, 22, 23]. Previous research indicated that 100% replacement of glass fibre with natural fibres would degrade the reinforcement strength of FRP bars, but partial replacement with natural biofibres may offer some benefit. In this study, glass/natural jute FRP bars were manufactured for reinforcing concrete structures. The tensile performance of FRP containing 0%, 30%, 50%, 70%, and 100% natural jute within the fibre portion, where the remaining volume was glass, was evaluated.

2. Experimental methods

2.1. Materials

Glass fibre was obtained from Hankuk Fibre Company (Milyang, Republic of Korea). The natural jute fibre used in this research was obtained from Nycontech Company (Seoul, Republic of Korea). Vinyl ester resin was purchased from Ashland Chemical (Covington, KY, USA). The properties of the material components, as specified by the manufacturers, are listed in Table 1. Natural jute fibre, having a lower tensile strength than E-glass fibre, is 52% as dense and similar elastic modulus in comparison with glass fibre (Table 1). Because natural jute fibre is less expensive than glass fibre and has little effect on the human body, natural fibre can replace synthetic fibre in certain applications. A major weakness of natural fibres is their hydrophilicity and resulting water sensitivity and weak binding/adhesion to most hydrophobic polymeric resins [3, 4, 6]. Thus, the surface of natural fibres must be conditioned for use in FRP bars. Accordingly, in this study, a silane coupling agent was used to treat the natural jute fibre surface [4, 6]. The polymer composite matrix is commonly composed of epoxy, vinyl ester, or polyester resins. Though vinyl ester resin, like polyesters, is degraded by OH$^-$ ions and is thus not an ideal tensile reinforcement material in concrete, it was nonetheless used here, as it is inexpensive and has been shown to be durable in previous studies of FRP composite materials [12].

| Mechanical properties | Vinyl ester resin | E-glass | Natural jute fiber |
|-----------------------|------------------|--------|-------------------|
| Tensile stress (MPa)  | 90               | 3,400  | 393               |
| Elastic modulus (GPa) | 3.4              | 71     | 55                |
| Specific modulus      | -                | 28     | 38                |
| Strain (%)            | -                | 4.79   | 0.71              |
| Fiber density (g/cm$^3$) | -            | 2.62   | 1.3               |

2.2. Pre-treatment of natural fibre

A silane coupling agent, γ-methacryloxypropyltrimethoxysilane, was used to strengthen the interfacial binding between the natural jute fibres and vinyl ester resin. γ-methacryloxypropyltrimethoxysilane was hydrolysed for 1 h after dilution with a cosolvent of methanol and distilled water (weight ratio 95:5). The pH of the solution was adjusted to 4.0 with acetic acid and the concentration of the silane coupling agent was fixed at 0.8 wt%. Natural jute fibre was then soaked in the hydrolysed solution for 30 min, removed, dried in an oven at 110°C, and allowed to dry completely at room temperature.

2.3. Glass/natural jute FRP bars bar preparation
Five kinds of glass/natural jute FRP bars were prepared at various volume ratios of natural jute fibre, glass fibre, and vinyl ester resin (table 2). A combination of pultrusion and braiding process was used to manufacture the tests specimens. PVA fibre was used in the braiding process to improve the bonding with concrete. Figure 1 shows the shape of the glass/natural jute FRP bars.

| No. of mix | Natural jute fiber (Vol. %) | Glass fiber (Vol. %) |
|------------|----------------------------|---------------------|
| No. 1      | 0                          | 100                 |
| No. 2      | 30                         | 70                  |
| No. 3      | 50                         | 50                  |
| No. 4      | 70                         | 30                  |
| No. 5      | 100                        | 0                   |

2.4. Test method

The tensile strength of the FRP bars was tested in accordance with ACI Subcommittee 440 K guidelines [17]. As FRP bars were difficult to secure in the test apparatus and they were easily broken by slippage between the specimen grip and FRP bar, the centre of the grip point was reinforced with a silica–epoxy mix to increase the surface friction between the grip and the composite bar. The grip measured 300 mm by 30 mm, and the glass/natural jute FRP bars were 800 mm by 5 mm. Tensile tests were performed using a displacement-adjustable universal tensile machine (UTM; Han Sin Gum Pung Company, Seoul, Republic of Korea), with a capacity of 1,000 kN at a loading speed of 5 mm min⁻¹.

The strain on the concrete FRP reinforcement bar was measured using a linear variable differential transformer (LVDT). The test was performed on five specimens. Figure 2 shows the tensile test apparatus.

3. Results and discussion

3.1. Tensile load–displacement behaviour

Generally, FRP reinforcing materials are brittle and exhibit linear elastic behaviour. Figure 3 shows the tensile load–displacement curves for the composite bars; the tensile–load behaviour exhibited nearly linear elasticity, up to a fibre volume fraction of 50% natural jute fibre. FRPs in which 70% of
the fibre was natural jute initially showed linear elastic behaviour, followed by plastic deformation. Glass/natural jute FRP bars prepared using 100% natural jute fibre displayed linear elastic behaviour. Numerous studies have examined the use of hybrid FRP bars for concrete reinforcement applications to promote ductile behaviour and to minimise or prevent material brittleness, a disadvantage of FRP bars [24-26]. Hybrid FRP bars, consist of multiple fibres, one or more with a high elasticity modulus and one with a low modulus [24-26]. The rigid fibre is destroyed upon application of a tensile load, while the flexible fibre shows ductile behaviour with some plastic deformation before rupture [24-26]. Carbon fibre has a high elasticity modulus, and glass or aramid fibre has a low elasticity modulus. Under an applied load to a hybrid of these two fibres, the carbon fibre is destroyed, and the glass fibre or aramid fibre secures the plastic deformation region until rupture [24-26]. In addition, plastic deformation may be promoted by reducing the fibre volume fraction of the high elasticity modulus fibre and increasing that of the low elasticity modulus fibre. FRP bars show linear elastic, or brittle, behaviour [24-26]. In the existing research on FRP composites, many research groups have achieved ductile behaviour using 30% rigid and 70% elastic fibre (having a high deformation rate). In this study, glass fibre and natural jute fibre were used in the FRP composite. The elasticity modulus of glass fibre (71 GPa) is 29% higher than that of natural jute fibre (55 GPa). Similarly, the tensile strength of glass fibre is 8.65 times that of natural jute fibre (3400 MPa vs. 393 MPa), and the deformation rate of glass fibre is 6.75 times that of natural jute fibre (4.79% vs. 0.72%). The difference in deformation rate makes sufficient plastic deformation after destruction of the glass fibre almost impossible; thus, for fibre volume fractions of 50%, 70%, and 100%, the natural jute fibre (low elasticity modulus) was destroyed earlier than the glass fibre (high elasticity modulus), regardless of the mix proportion, as indicated by the brittle behaviour. At a fibre volume fraction of 30% glass fibre, the initial elastic behaviour of the FRP composite was followed by plastic deformation and finally, rupture. The addition of natural jute fibre to the FRP composite appeared to delay the onset of plastic deformation, which was not prominent because the tensile strength and deformation rate of natural jute fibre are 1/8.65 and 1/6.75 those of the glass fibre, respectively. FRP bars containing 100% natural jute fibre displayed some plastic deformation when the load was reduced following linear elastic behaviour, but the tensile load required to induce plastic deformation was small. This plasticity results from the process used to manufacture the glass/natural jute FRP bars; they were braided with PVA fibre to form ribs for improved surface adhesion to concrete. As PVA fibre has little resistance after destruction of the natural jute fibre, it has negligible impact on the behaviour of any of the FRP bars. Thus, upon rupture, the reduction in load was so large that the PVA fibre was simultaneously destroyed. This was expected; PVA fibre was used for adhesive purposes only.

3.2. Tensile strength
Figure 4 shows that tensile strength decreased in proportion to the volume fraction of natural jute fibre. These results confirm previous observations; the tensile strength of hybrid FRP bars containing two or
Figure 4. Tensile strength of the glass/natural jute fiber reinforced polymer bars.

Figure 5. Fracture surface investigation of glass/natural jute fiber reinforced polymer bar after tensile strength tests: (a) Natural jute-0%, (b) Natural jute-30%, (c) Natural jute-50%, (d) Natural jute-70%, (e) Natural jute-100%

more fibres is known to decrease as the fibre volume fraction of the low elasticity modulus fibre (in this case, natural jute) increases. The tensile strength of the natural jute fibre used here is only 1/8.65 that of the glass fibre, and thus should significantly decrease the tensile strength of glass/natural jute FRP bars. For natural jute fibre volume fractions of 30%, 50%, 70%, and 100%, the corresponding tensile strength was 89.9%, 54.3%, 41.4%, and 16.5%, respectively, that of 100% glass fibre (1129 MPa). These results reveal a smaller impact of jute fibre than would be expected based on the difference in tensile strength; the glass/natural jute FRP bar containing 50% each glass fibre and natural jute fibre should show about 23.12% (1/4.325) of the tensile strength as that using 100% glass fibre. This is attributable to the difference in density between the two fibres; natural jute fibre is 1/2 as dense as glass fibre, so the number of fibre molecules doubles for the same volume. This larger number of fibres increases the tensile strength. FRP bars ruptured as a result of interfacial separation between the braided PVA surface-treated area and the inner portion containing the mixed glass/natural jute FRP composite (figure 5). This separation was more pronounced at high volume fractions of natural jute fibre. For example, there was almost no interfacial separation for FRP bars containing 0% and 30% natural jute fibre, but significant separation was observed for those containing 50%, 70%, and 100% natural jute fibre.

4. Conclusions
Glass/natural jute FRP bars were evaluated for use as a tensile reinforcement material in concrete structures. The tensile properties of the glass/natural jute FRP bars can be summarized as follows:

- The tensile load–displacement behaviour of the composite bars showed almost perfect linear
elasticity up to a fibre volume fraction of 50% natural jute fibre. For 70% natural jute fibre, the linear elastic behaviour of the glass fibre was evident to the point of rupture, followed by plastic deformation, which was minimal as glass fibre has high elasticity modulus, tensile strength, and deformation rate. For a fibre volume fraction of 100% natural jute fibre, linear elastic behaviour was observed.

- The tensile strength of glass/natural jute FRP bars decreased as the fibre volume fraction of natural jute fibre increased. This was attributed to the tensile strength of natural jute fibre, which is about 1/8.65 that of glass fibre. However, the tensile strength did not decrease linearly with the mix proportion of natural jute fibre is about 1/2 as dense as glass fibre, meaning the same volume contains twice the number of fibres.

- Glass/natural jute FRP bars ruptured because of interfacial separation between the PVA fibre surface-treated portion and the inner portion containing the mix of glass fibre and natural jute fibre. This trend was more prominent for large fibre volume fractions of natural jute fibre.

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