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Geopolymer-bamboo composite – A novel sustainable construction material

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HIGHLIGHTS

- Potassium-sodium geopolymer is reinforced with bamboo fibers and strips.
- Testing the geopolymer-bamboo composite yielded good to high flexural strength.
- SEM micrographs reviewed the interface between the fibers and the geopolymer matrix.
- Metakaolin geopolymer was cured at 50 °C for 24 h and set to dry for 7 days at room temperature.
- Room temperature cure was also achievable with the same system.

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ABSTRACT

In the pursuit of sustainable construction, regional natural materials can be used as a base for geopolymer processing. For higher strength achievement, this study uses mixed potassium-sodium polysialate siloxo-type geopolymer reinforced with bamboo fibers and strips. The composite geopolymer reinforced with bamboo fibers was used as a binder for the bamboo strips. Geopolymer was synthesized using metakaolin produced from kaolinite extracted from Amazonian soil, and microscopically compared to a commercial, highly reactive, Metamax metakaolin-based geopolymer. Amazonian kaolin was converted into metakaolin by calcination up to 700 °C. X-ray diffraction (XRD) analysis showed the resulting amorphous metakaolin to be 76% pure, with 24% crystalline quartz impurity. Four-point flexural and compressive strength testing of the geopolymer were carried out according to ASTM standards C1341-13 and C1424-10. Scanning electron microscopy (SEM) was used to investigate the microstructure and the interface. In addition, XRD was used to confirm the formation of geopolymer. Amazonian metakaolin geopolymer reinforced with bamboo is a potential green sustainable construction material with compressive strength ranging from: 23–38 MPa for micro bamboo fibers alkali treated (BF1A), 23–25 MPa for short BF alkali treated (BF4A), and 25–29 MPa for short BF water treated (BF4W). Flexural strength values for geopolymer reinforced with bamboo fibers ranged from: 4–8 MPa for BF1A, 7–8 MPa for BF4W, and reached 21–30 MPa for mixed BF1A and bamboo strip reinforcements.

1. Introduction

The term polymer refers to organic molecules with large number of repeating units. Geopolymers are obtained from the polycondensation of aluminosilicate solids, activated by an aqueous solution of alkali silicate. Such reactions produce poly-silicoaluminates or simply polysialates, these materials generally called "geopolymers", or inorganic polymers [1].

As a structural material, metakaolin-based geopolymers (MKGP) have several advantages when compared to ordinary Portland cement (OPC). They have twice the compressive strength, three times flexure strength, faster setting time, earlier strength development [2], lower CO_2 emissions [3–5], and higher temperature resistance [2,6]. However, pure geopolymers are brittle and have low fracture toughness and tensile strength, like ceramics. Hence, like OPC, reinforcements are added to make a composite material which has better fracture toughness and tensile strength.

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Duxson et al. [7,8] carried out extensive research on the relationships between composition, processing, microstructure and the properties of MKGP and found out that geopolymers with Si:Al mole ratio 2:1 provided a fully reacted geopolymer with the best mechanical properties. Tippayasam et al. [9] reported on potassium-metakaolin based geopolymer heat-treated. Gouny et al. [10,11] researched natural materials composites on the feasibility of a geopolymer binder to assemble wood and earth structures. Haider et al. [12] studied the stress-strain characteristics of high-(85 MPa) and low-(28 MPa) strength geopolymer synthesized with sodium and fly ash, revealing similarities to normal concrete. Pelisser et al. [13] characterized sodium metakaolin-based geopolymer with high flexural strength of 17.6 MPa, compressive strength of 64 MPa, and elastic modulus of 10 GPa.

Geopolymers are eco-friendly and sustainable materials with a low carbon footprint. In addition to the mineral reserves containing aluminosilicates, Brazil has many industrial processes that generate fly ash and other by-products as sources of aluminosilicates, so it has the raw materials necessary for exploitation of this technology in abundance. Moreover, the introduction of fibers, particles and strips of native or natural materials grown in the Amazon (such as bamboo) in the production of geopolymeric composites, promote higher strength, rigidity, and workability, generating green high-performance materials. The use of regional and local materials in the production of geopolymeric composites reduce environmental impacts and broaden their applications.

Nematollahi et al. [14] evaluated sodium, potassium and calcium fly ash-based geopolymer reinforced with polyvinyl alcohol (PVA) short fibers. The resulting sodium-based geopolymer compressive strength was 54.6 MPa. Adding by uniform dispersion 2 vol% of 40 μm by 8 mm long PVA fibers to the sodium-based geopolymer matrix increased the compressive strength to 63.7 MPa. Sodium- and potassium-based geopolymer composites yielded 11.5 and 5.4 MPa flexural strength, respectively. Natali et al. [15] investigated the added strength and ductility of four different short fibers (7-mm long high tenacity (HT) carbon, E-glass, PVA and polyvinyl chloride (PVC)) on sodium-metakaolin-ladle slag based geopolymer. The 7-day three-point flexure strength for unreinforced geopolymer was 6.9 MPa. Adding 1 wt% of 10 μm HT carbon, 10 μm E-glass, 18 μm PVA, and 400 μm PVC yielded 11.7, 9.0, 11.2, and 10.0 MPa, respectively.

Herbal biocomposites (natural fibers), have low density, low cost and low energy consumption, as well as neutralizing CO_2. Characteristics of bamboo fibers include: low cost, high strength and biodegradability; absorption of CO_2 and production of O_2 3 times more than other plants. In the pursuit of tough or semi-ductile and high strength green geopolymer composites, several researchers used natural fibers, such as basalt [16,17], corn husk [18], wool [19], jute [20], rice stem [21], fique (or sisal) [22] for reinforcement of metakaolin based geopolymer (MKGP). Adding 10 wt% of 13 μm by 6.35 mm long basalt fiber tows to potassium-based geopolymer composites yielded 19.5 MPa three-point flexure strength [16]. Increasing the chopped basalt fiber lengths to 12.7 mm yielded 27.1 MPa three-point flexure strength [17]. Sodium-based geopolymer reinforced with corn husk fiber bundles resulted in 14.1 MPa four-point flexure strength [18]. Sodium-based geopolymer reinforced with 5 wt% wool fiber bundles yielded 8.1–9.1 MPa three-point flexure strength [19]. Sodium-based geopolymer reinforced with 30 wt% untreated jute weave resulted in 20.5 MPa four-point flexure strength [20]. Potassium-based geopolymer reinforced with 6.4 wt% rice stems yielded 18.4 MPa three-point flexure strength [21]. Potassium-based geopolymer reinforced with 30 wt% alkali-treated fique fibers yielded 11.4 MPa four-point flexure strength [22]. Up to this date, we found no published work on MKGP reinforced with bamboo fibers.

In this manuscript, mixed sodium and potassium geopolymer reinforced with chopped bamboo fibers was used as a binder for bamboo strips. The aim of this research was to develop high performance green-sustainable technologies, using local materials cultivated in the Amazon (like bamboo). The building components are designed to be innovative, low-carbon emission elements, in production and utilization. This project also aims to develop a new generation of sustainable building materials such as reinforced crushed bamboo for panels and blocks, ceramic-like composites which take advantage of the low-temperature synthesis of geopolymers and their superior mechanical properties as compared to normal cement. Kaolinite clays and amorphous silica from the Amazon region will be the low cost starting powders.

2. Experimental procedures

2.1. Bamboo fibers and strips processing

An Amazonian tropical bamboo specie *Guadua angustifolia* was selected based on abundance, accessibility, mechanical properties, durability and commercial size criteria [23]. Four-year old *Guadua* culms were collected from a research plantation area [24,25], in Manaus, Brazil, and immersed in water for three days for better machine workability. The mean basic density of the *Guadua* culms were determined as $0.59 \pm 0.04\ g/cm^3$. The green bamboo culms (Fig. 1(a)) were chopped through a chipper PZ8 Pallman and the chips were transformed into fiber bundles through a Hammer Mill Bison. The bamboo fiber bundles (BFs) were air-dried, and filtered by an Allgaier sifter machine through a mesh #4 (12.51–40 mm) (producing short bamboo fibers, BF4) and a mesh #1.25 (producing particulates or micro bamboo fibers, BF1), as illustrated in Fig. 1 (b)–(c). The main chemical constituents of bamboo are around 60 wt% cellulose, 32 wt% lignin and 8 wt% hemicellulose [26]. Minor constituents are resins, tannins, waxes, inorganic salts. Bamboo fiber bundles and particles cut as-received were characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD) and thermogravimetric analysis (TGA). In addition, bamboo strips (BSs) were cut and planed to size to compose the architecture of the geopolymer composites studied. The BSs were water treated for starch removal, and set to dry in a solar kiln at 40 °C [27].

Fig. 1. (a) Water-treated bamboo culms; (b) mechanically attained air-dried fiber bundles; (c) washed BFs reinforcement just before use; (d) BSs reinforcement.