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Compressed soil blocks: Influence of fibers on flexural properties and failure mechanism

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HIGHLIGHTS

- The polypropylene fibers improved the post-crack performance of the beams.
- Higher peak loads were reached at fiber contents of 0.6% and 0.8%.
- Both fiber pullout and fracture was observed during specimen testing.

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ABSTRACT

Soil blocks are sustainable, low-cost, masonry materials that exhibit low resistance to bending. This study focused on experimentally investigating the influence of polypropylene fibers on the flexural performance and failure mechanism of cement stabilized soil blocks. Specimens were produced with different fiber mass proportions for comparison with specimens without fibers. Test results showed an improvement in post-crack flexural behavior and toughness of the fiber-reinforced specimens compared to the unreinforced ones. Depending on fiber content, specimens exhibited either a deflection softening or deflection hardening behavior during testing. Failure of specimens was characterized by both fiber fracture and pullout.

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1. Introduction

The use of locally available materials for construction is highly encouraged by proponents of sustainable construction. Earthen construction is generally considered sustainable because it involves the use of indigenous soils and locally available materials thereby reducing transportation cost and the use of manufactured materials [1,2]. There is a resurgence in the use of earthen construction materials mainly due to their lower embodied energy and cost compared to mainstream walling materials like fired bricks and concrete masonry units (CMU) [3–5]. However, durability and resilience are important attributes that cannot be decoupled from sustainability in the built environment. Some disadvantages of earthen masonry/construction systems include poor seismic performance if not properly designed and constructed, code restrictions on building height and width where applicable, and durability issues associated prolonged moisture exposure [6]. Some of these concerns are being addressed by exploring the use of compressed stabilized soil blocks, which are stronger and more dimensionally stable compared to the traditional adobe block [7].

The use of stabilizers like ordinary Portland cement (OPC) for soil block production often improves strength and lends blocks properties that enable adherence to modern building code requirements [7,8]. There are ongoing research efforts aimed at improving the properties of soil blocks due to perceived and real strength and durability limitations [9]. An area drawing a lot of interest in soil block production is the inclusion of fibers into matrices for block production. The inclusion of stabilizers and fibers in soil blocks enhances the engineering properties and performance characteristics of blocks [9,10]. Generally, earthen materials reinforced with fibers show an improved performance in resisting cracks and crack propagation, increase in compressive strength (depending on soil and fiber type) and increase in tensile strength [5,11,12]. Usually very low percentages of fibers are needed to achieve optimal performance of fiber-reinforced soil blocks [9].

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OPC stabilized soil blocks exhibit characteristics typical of cementitious matrices; they are quasi-brittle and have low tensile strength and strain capacities. A practical means of enhancing the performance of such matrices is the inclusion of various types of fibers to enhance ductility, strength, toughness, and resistance to impact loads [13,14]. An understanding of fiber, matrix, and fiber-matrix interaction is therefore essential to using fibers to enhance the performance of cementitious matrices. This is because failure of fiber–reinforced cementitious matrices largely depends on fiber matrix interactions and the pullout (slip) characteristics between fibers and matrices [15,16].

Natural fibers are considered the most economical fibers to use for the production of earthen masonry materials. However, there are concerns over fiber quality and degradation, the hydrophilic nature of fibers, and fiber dispersion in matrices when natural fibers are used [12,17]. The net impact of chemical reactions on the strength properties of natural fiber compressed soil blocks, especially durability due to the effect of the alkaline environment present in OPC is a subject that needs to be further investigated before scaling up the use of natural fibers in soil block production [17]. When synthetic fibers are used for compressed soil block production, they are often derived from chopped post-consumer plastic waste products. This introduces the possibility of variations in block quality and strength properties especially when fibers derived from different waste plastic materials are used in the same mix [5]. The fiber choice for this study was to promote replicability and ensure consistency in results. A critique often leveled against earthen masonry materials is the lack of consistency in test results which leads to a lack of confidence in the material. Predictability of results is needed to allow engineers and inspectors to gain the needed confidence in earthen masonry materials [18].

This paper evaluated the technical feasibility of using PP fibers as reinforcement in soil block production. Beams were produced with PP fibers and the influence of the fibers on flexural performance and composite failure mechanisms evaluated. The paper also determined best practices for incorporating PP fibers into soil-cement mixes for soil block production. Failure surfaces of beam specimens broken during flexural strength testing were analyzed using scanning electron microscopy (SEM) to help understand how fibers prevent catastrophic failure and restrain cracks from propagating. A micro-level understanding of fiber-matrix interactions can help with the formulation of appropriate macro-level systems for enhanced performance. The research presented in this paper is part of a larger research effort aimed at developing fiber-reinforced masonry systems for high wind regions in the United States. Some of the findings of the larger research effort have or will be reported in other publications [5,19–21].

2. Materials and methods

2.1. Materials

The fibers used for specimen production are commercially available macro synthetic polypropylene fibers, "MasterFiber MAC Matrix" obtained from the BASF Corporation. The fibers are composed of two circular filaments cross-linked into a single "stick-like" fiber with an embossed surface (depths from peak to valley of about 0.005 to 0.006 mm) to provide mechanical anchorage between the fibers and matrices (Fig. 1). The physical properties of the fibers as provided by the manufacturer is presented in Table 1. The grain size distribution of the soil used in this study was determined using the American Association of State Highway and Transportation Officials (AASHTO) soil classification system M 145/ASTM D3282 (Table 2).

2.2. Specimen preparation

There are no standard protocols for producing and testing soil blocks. Additionally, there are no standard protocols for fiber addition into soil-cement matrices for block production. The inherent variability in soil properties makes it important to adopt a systematic approach to producing quality soil blocks [20]. Adequate mixing techniques need to be developed to encourage large scale production of fiber-reinforced soil–cement structures [22]. In order to develop an appropriate mixing protocol for incorporating PP fibers into soil-cement matrices used for soil block production and also to promote replicability of test results, flexural beams were produced for evaluation of flexural properties.

Matrix mixing was done using a concrete mixer starting with a dry mix of soil and OPC. The fibers were gradually introduced into the dry mix of soil and OPC in batches by randomly sprinkling them into the dry mix at a rate of about 0.045 kg every one minute. After the last batch of fibers was introduced, mixing continued for an additional 3 min. The dry mix was watered gradually as mixing continued. Mixing was halted after about 10 min of wet mixing. The fiber–reinforced matrices were produced with fibers at 0.2, 0.4, 0.6, 0.8, and 1.0 mass fractions based on the findings of Donkor [19]. OPC content and water-cement-ratio was kept at 8.0% and 0.17 respectively.

Compaction of the wet mix was done in a heavy-duty steel mold using a Test Mark CM-500 series compression machine with a maximum compression capacity of 2224 kN. Each beam was produced using 8.62 kg of matrix. The nominal dimension of beams produced was 413 mm (length) × 102 mm (width) × 102 mm (height) (Fig. 2). Beam sizing was per ASTM 106, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete [23] to provide a span to depth ratio of 3.0 for adequate flexural performance evaluation. The beams were kept under plastic sheets and moist cured (sprayed with water) for the first 7 days. The beams remained under the plastic sheets without further moist curing for the next 21 days. Flexural testing was undertaken 28 days after production.

2.3. Test procedures and analysis methods

Flexural testing of beams was undertaken using a Tinius Olsen compression machine with a maximum load capacity of 400 kN. Testing was done according to ASTM 106 [23]. Beams to be tested were rotated through 90° from their casting position before testing to minimize the influence of casting direction on results. Leather shims were placed on the contact surface of specimens to provide an even surface and eliminate gaps during load application. Beams were simply supported and subjected to third-point loading. Linear variable displacement transducers (LVDTs) were mounted on either side of beams to record mid-span deflection. Loading was deflection controlled at a rate of 0.25 mm/min. The test set-up is shown in Fig. 3.

Generally, the flexural behavior of fiber reinforced cementitious composites is either deflection-softening or deflection-hardening (Fig. 4). Composites that undergo deflection-hardening exhibit a higher load carrying capacity after first-peak load (P_1) is reached [24]. Deflection-softening composites on the other hand exhibit a lower load carrying capacity after P_1 is reached. With deflection-softening, P_1 is equal to peak load (P_p).

The load versus net deflection curves obtained during testing were used to calculate first-peak strength (f_1) and peak strength (f_p) (Eq. (1)), equivalent flexural strength ratio ($R^D_{T,150}$) (Eq. (2)) and residual strength at deflections of $L/600$ (f^D_{600}) and $L/150$ (f^D_{150}). Residual strength is the ability of the fiber–reinforced beams to sustain load after first crack at specified deflections.

$$f_{1/P} = \frac{P_{(1/P)}L}{bd^2} \quad (1)$$

$$R^D_{T,150} = \frac{150.T^D_{150}}{f_1 b.d^2}.100\% \quad (2)$$

where; f_1 = first–peak strength, f_P = peak strength, P_1 = first–peak load, P_p = peak load, $R^D_{T,150}$ = equivalent flexural strength ratio, T^D_{150} = flexural toughness (area under load the load-deflection from 0 to $L/150$), b = average width of specimen at the fracture, and d = average depth of specimen at the fracture.

An SEM JSM 6400 microscope was used to analyze the fractured surfaces of fiber-reinforced beams broken during flexural strength testing. Micrographs of the fractured surfaces were captured to enable evaluation of the failure mode of the fibers, an important parameter for the evaluation of energy absorption of fiber-reinforced cementitious composites [25].

3. Results and discussion

3.1. Flexural response

Table 3 summarizes the test results of the beams at different fiber contents. Failure of beams was characterized by ether a single crack or multiple cracks. Most of the cracks (single or multiple) initially emerged from the upper middle third o beams and propagated downwards without going outside the middle third. With a few of the specimens, crack formation was initiated within the upper middle third and beams and propagated

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