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Ductility enhancement of autoclaved cellulose fiber reinforced cement boards manufactured using a laboratory method simulating the Hatschek process

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HIGHLIGHTS

- Ductility of FC boards can be altered by modifying the cementitious matrix mixture.
- Reducing the density of the FC board is an effective method to increase ductility.
- Replacing cement with fly ash increases the ductility and reduces the matrix strength.
- Replacing fly ash with silica quartz reduces the ductility.
- Fiber mineralization was not observed in autoclaved FC boards.

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ABSTRACT

Autoclaved fiber cement (FC) boards manufactured using the Hatschek process are commonly used as building products such as siding and shingles. Despite their advantages, these products may exhibit low ductility and volume instability. A common, yet expensive, method for improving ductility is increasing the fiber content. In this study, a procedure to manufacture FC boards in the laboratory was introduced, and alternative economical methods for increasing the boards' ductility were investigated. Ductility was measured using a 3-point or 4-point bending tests, while the microstructure of the boards was studied using scanning electron microscopy. The results show that ductility of FC boards was improved by reducing their matrix tensile strength. This was achieved by reducing the density (increasing porosity) of FC boards or by partially replacing Portland cement with fly ash. Fiber mineralization was not found to be the cause of brittleness in the investigated FC boards.

1. Introduction

Thin (≈8 mm) autoclaved cellulose fiber cement (FC) boards are a special class of fiber-reinforced cementitious composites. They are widely used in residential and commercial building construction, as siding, ceilings, floors, roofs and tile backer boards. For example, FC siding is commonly used as a replacement for wood siding, as it is less expensive and more durable, and has lower maintenance costs. Due to a relatively high fiber content (≈8% weight fraction of solids) and to speed up the manufacturing, FC boards are made in a production line and using a special procedure known as the Hatschek process [1]. The process involves spraying or straining a dilute slurry of fibers, cementitious materials and aggregates (e.g., quartz powder) over a fine sieve, which collects the solids in saturated condition and form thin layers. The initial water to solid mass ratio of the slurry often exceeds 10. The thin layers are stacked on top of each other until a desired board thickness is reached. The resulting composite is then vacuum dewatered and pressed to drain the excess water [2]. As a result, unlike common cement-based materials, water to cementitious materials ratio (w/cm) is not constant during the Hatschek process and depends on the w/cm of the slurry, thickness and number of the stacked layers, the vacuum and press pressure, and duration of dewatering. The boards are subsequently autoclaved at high pressure (0.8 to 1.0 MPa) and high temperature (170 to 200 °C) to

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accelerate curing and strength gain. The boards are often ready to be shipped to consumers a day after production.

Despite their advantages, FC products are prone to a few performance concerns, including low ductility and potential volume instability. Ductility is defined as the ability of the material to undergo large deformations before macro-cracking and failure occurs. Specifically, brittleness (lack of ductility) may cause difficulties in handling, cutting and nailing FC boards. FC boards with low ductility are sensitive to small deformations and may crack due to moisture changes. Further, FC boards may lose ductility over time. An existing solution to address the low ductility issue is increasing the fiber content. However, fibers are the most expensive component of FC composites, and as such, this solution is not economically favorable.

Volume stability is another important parameter, especially in FC siding, since these products are used on the exterior of buildings and are exposed to drying. Since FC siding is restrained longitudinally on the wall, large carbonation and drying shrinkage deformations can occur and result in development of tensile stresses and cracking of the siding. To improve volume stability, quartz powder is often used as aggregate/filler and pozzolan in production of FC boards. Quartz powder promotes formation of tobermorite (a crystalline form of C-S-H) at autoclave temperatures, and tobermorite is more stable and less prone to carbonation in comparison with amorphous C-S-H [3–5].

The focus of the present study is to explore alternative methods to increase the ductility of FC boards without increasing their fiber content. Specifically, two hypotheses are evaluated in this research:

I. Ductility of autoclaved cellulose fiber cement (FC) boards can be increased by reducing the tensile strength of their matrix, which can be achieved by reducing the composite's density (i.e., increased porosity), and by reducing its Portland cement content in replacement with fly ash.
II. Low ductility of FC boards is primarily caused by fiber mineralization (introduced below).

2. Relevant literature

Given that autoclaved Hatschek fiber cement (FC) board is a niche class of fiber-reinforced cementitious composites, there is limited available literature on their properties and methods to improve their performance. Major manufacturers perform in-house research, whose findings are generally not publically available, to protect their intellectual property.

Brittle failure is often observed when fibers fracture in tension before they are pulled out of the cement matrix [6,7]. Past researchers have studied the mechanisms behind brittleness of FC boards [8–12]. Mohr et al. [8] suggested decomposition of fibers in high alkalinity, and fiber mineralization (i.e., precipitation of hydration products, mainly portlandite, within the fiber structure) to be the likely causes of brittleness. They tested cement paste samples, reinforced with kraft pulp softwood fibers, which were exposed to accelerated wetting and drying cycles. They observed a rapid reduction in toughness and maximum strength (by approximately 50%) after only 5 cycles. Similar results were found by Gram [13], Ziraba et al. [14], Canovas et al. [15], and others [9,10,16–21].

Mohr et al. [8] observed a reduction in the pullout length of fibers after exposure to wet/dry cycles. They proposed a progressive series of mechanisms to explain the decreased fiber pullout lengths: 1- initial fiber–cement debonding due to fiber shrinkage during drying, 2- precipitation of relatively low-strength hydration products (e.g., secondary ettringite) within this new void space, and 3- fiber mineralization by the re-precipitation of hydration products, likely portlandite, within the fiber cell wall structure. However, they hypothesized that the first two mechanisms do not occur in the Hatschek FC boards, and only fiber mineralization is likely responsible for their increased brittleness [22]. Several approaches were investigated in previous studies in attempts to mitigate fiber mineralization. Fiber coating and impregnation were studied by Gram [13], Ziraba et al. [14] and Canovas et al. [15] using water blocking and repelling agents (such as epoxy and asphalt). Their result showed some level of reduction in the composite embrittlement.

In addition, durability and aging mechanisms of autoclaved cellulose fiber reinforced cement sheets have been studied by a number of researchers [6,7,23,24]. Increasing the fiber content have been shown to effectively increase the ductility of the fiber-reinforced boards. Khorami and Ganjian [25] studied the effect of fiber content on flexural behavior of fiber reinforced cement composites. They suggested a fiber content of 8% (by weight) as optimum fiber content.

3. Theory

Fiber reinforced cement composites can be categorized into two types, based on their fiber content: low-volume and high-volume fiber composites. Each type behaves differently under tension [14,26]. Fig. 1 illustrates the difference. In low-volume fiber cement composites, after the matrix fails, the number of fibers that exist in the failure section is not enough to transfer the load across the failure section. Therefore, immediately after the matrix fails, fibers fail as well, and macroscopic failure of the composite occurs. In high-volume fiber cement composites, after the matrix fails, fibers transfer the load across the failure section, which allows the composite to carry higher loads. There is a threshold fiber content that distinguishes these two different behaviors. This threshold is known as the critical fiber volume fraction and depends on several parameters, such as fiber-matrix bond strength, fiber strength and elastic modulus, and matrix strength and modulus.

A number of researchers studied the strain hardening and multiple cracking behavior in fiber cement composites, and presented formulation to predict the critical fiber volume fraction. Naaman [27] used composite mechanics and concluded that multiple cracking occurs when post-cracking strength is larger than the composite's cracking strength (this is close to but not exactly the same as the matrix tensile strength, as discussed below). The process can be explained in different stress levels. When the composite's cracking strength is reached, the composite cracks but does not fail since the fibers carry the load across the crack. However, when the applied stress is higher than the cracking strength, the composite cracks in multiple locations and this process continues until fibers frac-

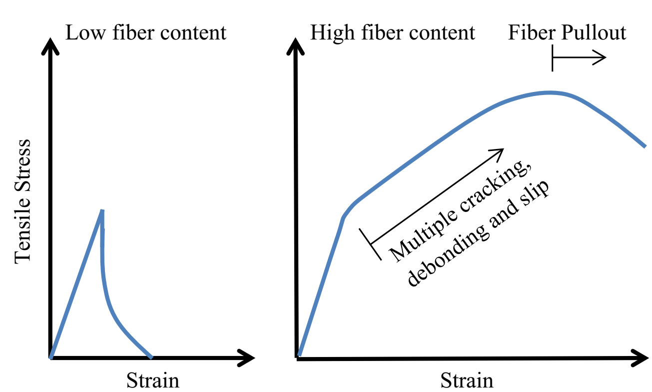

Fig. 1. Effect of fiber volume fraction on tensile strength of FC composites [26].