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Evaluation of normal-weight and light-weight fillers in extruded cellulose fiber cement products

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Abstract

Extruded fiber cement products offer advantages in terms of the versatility of section profiles, end product performance characteristics, and production throughput. Wood fibers offer a desirable balance of performance and cost as reinforcement in extruded wood fiber cement products. The research reported herein assessed the effects of normal-weight (silica sand) and light-weight (expanded shale) fillers on mechanical, physical and durability characteristics of extruded cement products reinforced with softwood, hardwood, and recycled fibers. Fillers caused improvements in moisture resistance and durability of extruded wood fiber cement products. Their presence, however, lowered the flexural strength and nailability of fiber cement boards.

Keywords: Extrusion; Wood fibers; Cement; Fillers; Mechanical properties; Durability

1. Introduction

Wood fiber cement is part of a new generation of engineered products preceded by wood I-beams, laminated veneer lumber, parallel strand lumber, laminated strand lumber, medium density fiberboard, and Oriented Strand Board (OSB). Compared to competing products, wood fiber cement is at the early stage of its diffusion curve (Fig. 1); at this stage, technological innovations play a vital role in supporting market penetration.

The demise of asbestos brought about the collapse of fiber cement industry in the United States. In Europe, Japan and Australia, on the other hand, the industry managed to replace asbestos (largely with wood fibers) in cement products [1]. The global influence finally led to the emergence of wood fiber cement industry in the US in 1990s [2]. The century-old Hatschek (slurry-dewatering) process, originally developed for asbestos cement, now fully dominates the production of wood fiber cement in the United States [3]. While the Hatschek system has its role to play within a slate of wood fiber cement technologies [4], its absolute predominance in the United States cannot be justified strictly based on its merits. End products of the Hatschek processing system suffer from lack of freeze-thaw durability in moist environments, relatively high sorption rate and permeability, serious limitations on profile and thickness, and limited embossing depth [4,5].

Traditionally, wood fiber cement processing systems have been categorized as wet or dry, depending on the moisture content of their fresh mix [4,6]. Hatschek, when compared with other wet processing systems (e.g., flow-on, Fourdrinier single-layer, and batch forming systems), offers advantages in terms of the dimensional stability of end products [4]. Commercially

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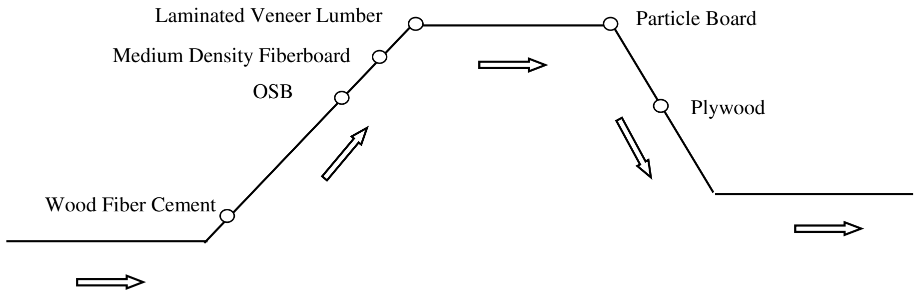

Fig. 1. Diffusion curves of wood fiber cement and other engineered products [1].

prevalent dry processes (mainly the cement-bonded particleboard system) involve batch-type pressing and lack the efficiency of continuous (e.g., Hatschek) systems; their dimensional stability is also a concern. The global trends indicate that cement-bonded particleboard also has its role to play within the slate of wood fiber cement technologies [4].

Recent technological developments in the field of wood fiber cement are looking beyond the traditional wet and dry processing systems. Extrusion presents an alternative mass production system for processing of wood fiber cement products [7]. Extrusion has strong attributes for overcoming the shortcomings of Hatschek and other conventional processing systems of wood fiber cement.

With a relative cease of manufacture and a much cleaner production, extrusion was found to be a suitable means for making cement composite with up to 8% fibers by weight [8]. Comparison between extruded and cast fiberboard revealed that the extruded produces were better in strength, stiffness, toughness, fiber distribution, fiber orientation, and bond of fiber with matrix, even in the presence of a higher percent air voids [9]. It was also found that sand content had significant effect on toughness but decreased the mechanical properties of the fiber-reinforced cement composites [10,11]. Shah and Shao [12] succeeded to fabricate fiber reinforced cement-based composite products, using the extrusion technology, with a tensile strength of 7 MPa and exhibit strain hardening behavior with a strain of 0.8% and more; however in the extruded composites, shorter fibers improved the performance [13]. It was also found that the use of fly ash had a negative effect on the mechanical performance of cast products, but a positive effect on the performance of extruded products (with long fibers) [14]. In general, it was concluded that the extrusion process improves the mechanical performance of cement composites [15].

2. Materials and methods

The basic mix ingredients for extrusion of wood fiber cement products were as follows: Type I Portland cement; silica fume, methyl cellulose, hydroxyethyl cellulose, high-range water reducer, wood fiber and water. Silica sand or light-weight aggregate was incorporated into some mixtures. The silica fume/cementitious ratio was fixed at 0.40 by weight (where cementitious refers to cement plus silica fume); the silica fume had fineness (% +45 μm) of 0.76%, loss on ignition of 3.16%, and bulk density of 0.286 g/cm^3. The high-range water-reducing admixture (ASTM C 494 Type F) was used at 0.83 l per 100 kg of cementitious materials (cement plus silica fume); this dosage falls within manufacturer's recommended range (0.65–1.6 l per 100 kg of cement). Three weight ratios of wood fiber-to-cementitious materials (cement plus silica fume) were used in this investigation: 0.05, 0.10, and 0.15. Methyl cellulose (cellulose ether) was an important constituent of the extrusion mix, contributing to the dispersion of fibers and also to the retainment of water and reduction of friction during extrusion. The methyl cellulose/cementitious (weight) ratios were 0.015, 0.020, and 0.030 at fiber/cementitious ratios of 0.05, 0.10, and 0.15, respectively. The hydroxyethyl cellulose (250,000 molecular weight) was used at 0.002, 0.003, and 0.004 s by weight of cementitious materials for fiber/cementitious ratios of 0.05, 0.10, and 0.15, respectively. The water/cementitious (weight) ratios were 0.58, 0.81, and 1.08 for fiber/cementitious ratios of 0.05, 0.10, and 0.15, respectively; this difference is ascribed to the absorption capacity of each fiber type.

Two types of filler (silica sand and light-weight aggregate were used in this investigation). The light-weight aggregate was expanded shale with specific gravity of 1.19 and average particle size of about 50 μm; the silica sand had an average particle size close to 150 μm. Silica sand and light-weight aggregates were added to the matrix at 25% and 1.1%, respectively, by weight of cementitious materials (cement plus silica fume).

The wood fibers used in this investigation were softwood kraft pulp, hardwood kraft pulp, and recycled pulp produced from magazine paper. The softwood (southern pine) kraft pulp used in this investigation had an average length of 3.3 mm and an average diameter of 37 μm; the hardwood (maple & birch) kraft pulp had an average length of 1.2 mm and an average diameter of 26 μm. The virgin fibers were not fibrillated before use in the extrusion mix. The recycled fibers were a blend of softwood and hardwood with average length of 1.4 mm; these fibers were obtained from magazine paper in a dry process which, when compared with wet recycling processes, is expected to induce more damage to fibers. A minimum of three replicated specimens were tested in each unaged and aged condition for all mix designs considered.

Preparation of the mix involved separate mixing of cementitious materials with 25% of methyl cellulose in a mortar mixer (to which the fillers were then added and thoroughly mixed), and high-speed mixing of water first with 75% of methyl cellulose, all of ethyl cellulose and high-range water reducer, and then with fiber. The wet fiber mix was then added to the dry mix in mortar mixer, and mixed until a homogenous blend was achieved.

A laboratory-scale de-airing ceramic extruder (Fig. 2) was used in this investigation. The de-airing auger has an outside diameter of 76 mm; the exterior diameter of the extrusion auger ranges from a maximum of 102 mm at the beginning to a minimum of 76 mm at the die. The lengths of the de-airing and extrusion augers are 171 and 305 mm, respectively. The auger extruder speed used herein was 15 rpm.

The die used with the extruder for production of flat specimens with 60 mm width and 8 mm thickness is shown in Fig. 3; this die had a width comparable with the barrel diameter of extruder. Hence, its main function was to reduce the thickness of the fresh product from about 60 mm (in barrel) to 8 mm. The die had a slope of 24°, with a 100 mm long flat finishing part.

Extruded fiber cement products were maintained at 22 °C and 100% relative humidity for 8 h, and then subjected to steam curing at 60 °C for 16 h. The products were then stored at 22 °C and 50% relative humidity for 14 days before they were tested. The test procedures conducted in this investigation generally followed

Fig. 2. The used auger extruder (with barrel removed).

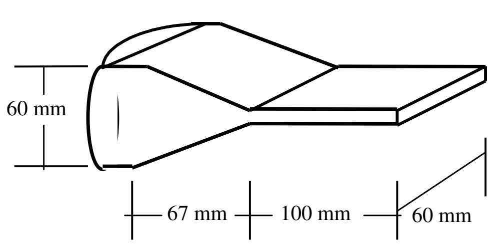

Fig. 3. Die geometry.

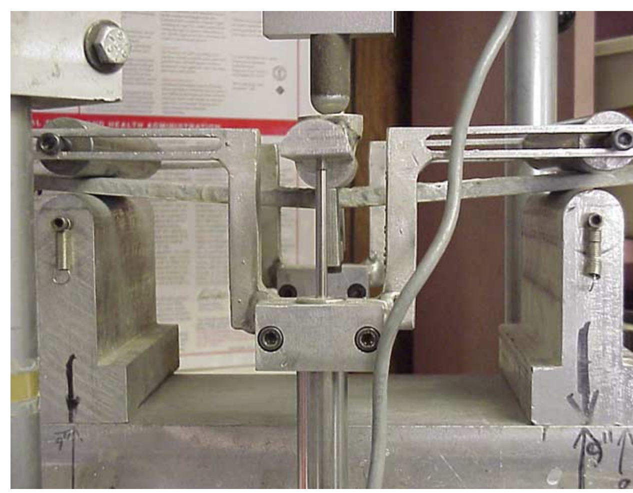

Fig. 4. Flexure test set-up.

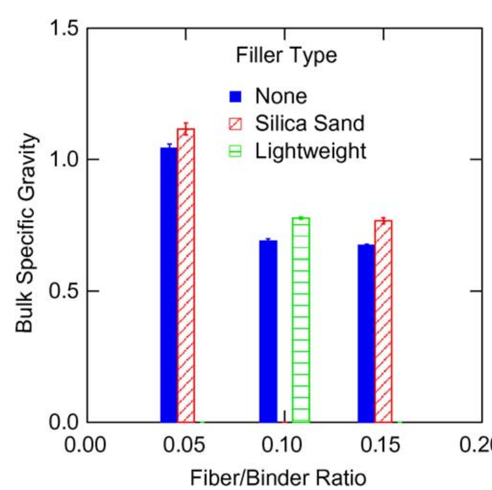

Fig. 5. Bulk specific gravity test results (means and standard errors).

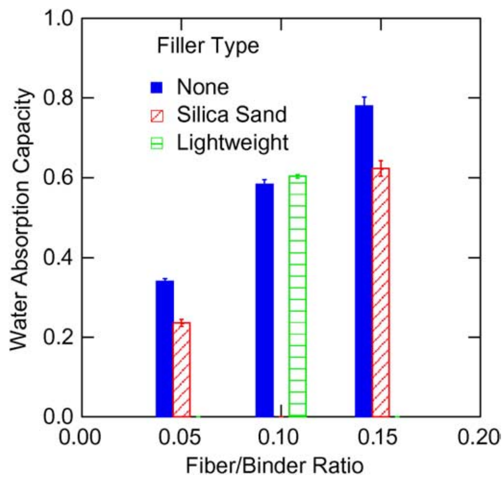

Fig. 6. Water absorption capacity test results (means and standard errors).

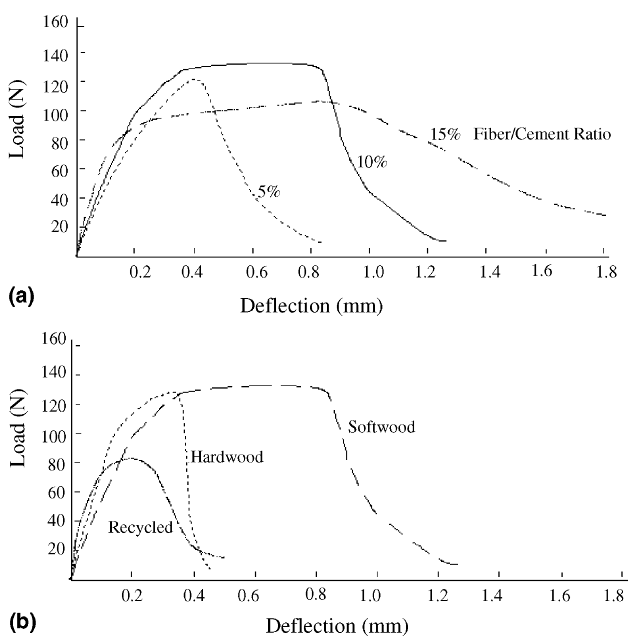

Fig. 7. Typical flexural load–deflection behavior of extruded wood fiber cement sheets. (a) Cement boards reinforced with softwood fibers at different fiber contents and (b) cement boards reinforced with different fibers at 10% fiber/cement ratio.

ASTM D 1037 and ASTM C 1185 procedures. Unaged extruded fiber cement products were subjected to the following tests (three replicated specimens were subjected to each test): flexure (Fig. 4) by center-point loading on a span of 230 mm (with specimen width of 60 mm); flexure in saturated condition (after 48 h of immersion in water at 22 °C); water absorption capacity; and bulk specific gravity. Three accelerated aging conditions were considered: (1) 30 cycles of wetting and drying (ASTM C 1185); (2) 300 cycles of wetting and drying in water (ASTM C 666); and (3) 56 days of immersion in warm (60 °C) water. After accelerated aging, the specimens were stored at 50% relative humidity and 22 °C before they were tested in flexure. Three replicated samples were subjected to accelerated aging and flexure testing. Finally, the nailability of extruded wood fiber cement products was judged in air-dried condition through observation of their resistance to cracking during nail application, with a ranking of "one" indicating excellent nailability and "zero" indicating very poor nailability.

3. Experimental results and discussion

The type of wood fiber did not have statistically significant effects of the bulk specific gravity and water absorption capacity of extruded wood fiber cement products. Hence, the effect of fillers on these properties was assessed neglecting the effect of fiber type. Figs. 5 and 6 summarize the bulk specific gravity and water absorption capacity test results for extruded fiber cement sheets with different fiber types and fiber/cementitious ratios.

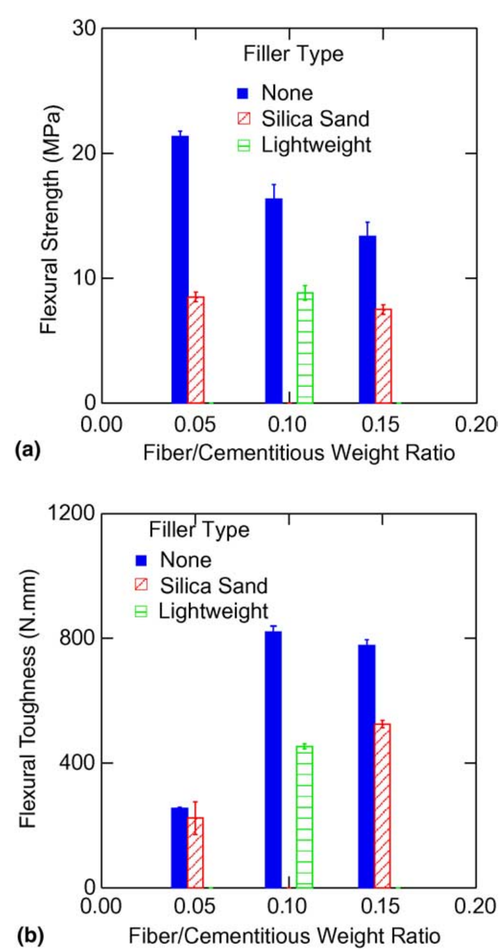

Fig. 8. Effects of light-weight and normal-weight fillers on flexural performance of extruded fiber cement products with softwood fibers (means and standard errors). (a) Flexural strength and (b) flexural toughness.

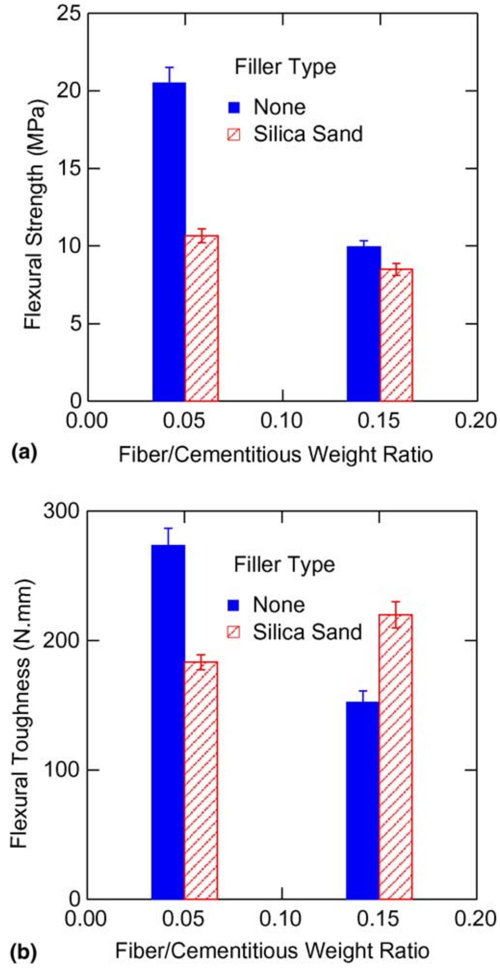

Fig. 9. Effects of light-weight and normal-weight fillers on flexural performance of extruded fiber cement products with hardwood fibers (means and standard errors). (a) Flexural strength and (b) flexural toughness.

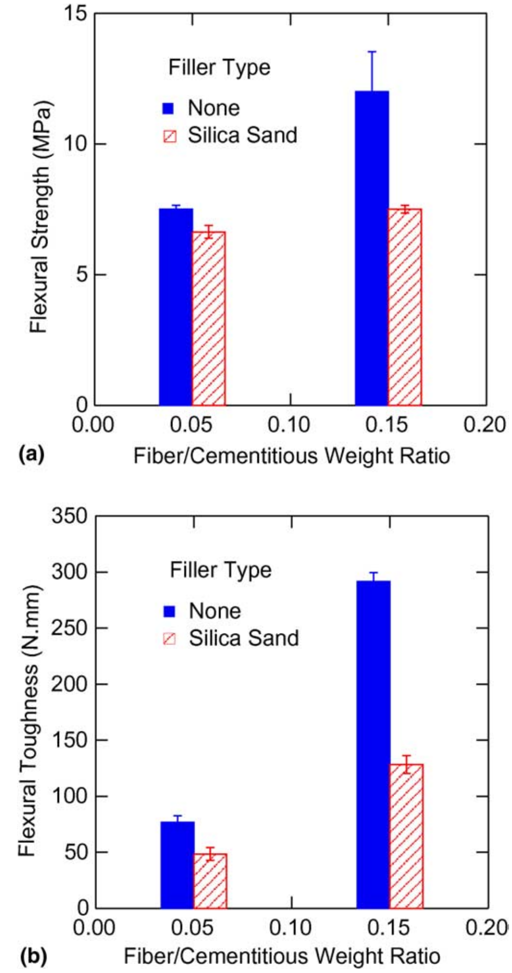

Fig. 10. Effects of light-weight and normal-weight fillers on flexural performance of extruded fiber cement products with recycled fibers (means and standard errors). (a) Flexural strength and (b) flexural toughness.

Increasing fiber contents are observed to lower the bulk specific gravity and raise the water absorption capacity of extruded fiber cement products. This suggests that the level of compaction in extrusion process decreases with increasing fiber content. The introduction of silica sand slightly increases the bulk specific gravity and reduces the water absorption capacity of extruded fiber cement products. Light-weight aggregate effects are relatively small, it did not show any significant effect on bulk specific gravity but a slight increase in water absorption capacity.

Fig. 7 presents typical flexural load–deflection curves for extruded fiber cement sheets reinforced with softwood, hardwood, and recycled fibers. These curves were characterized by tensile stress at peak flexural load (flexural strength, MPa) and total area underneath the load–deflection curve (flexural toughness, N mm). Fig. 7 suggests that increasing softwood fiber content from 5% to 15% (fiber/cementitious weight ratio) increases toughness of the system; flexural strength, however, increases slightly (5% increase in average) as fiber content increases from 5% to 10%, and then decreases (15% decrease in average) with fiber content increasing to 15%. Fig. 7b indicates that softwood fibers provide balanced improvements in flexural strength and toughness; hardwood fibers (with shorter length) are more effective, when compared to recycled fibers, in increasing flexural strength than toughness. The recycled fibers render less reinforcing effects than both softwood and hardwood fibers. The general trend observed here are similar to those observed with wood fiber cement products subjected to other processing conditions [12].

Figs. 8–10 summarize the effects of normal-weight and light-weight fillers on flexural strength and toughness of extruded wood fiber cement products incorporating softwood, hardwood, and recycled fibers, respectively. Fillers are observed to generally cause a drop in flexural strength and, to a somewhat lesser extent, in flexural toughness. For instance, light-weight and silica sand fillers decreased flexural strength by

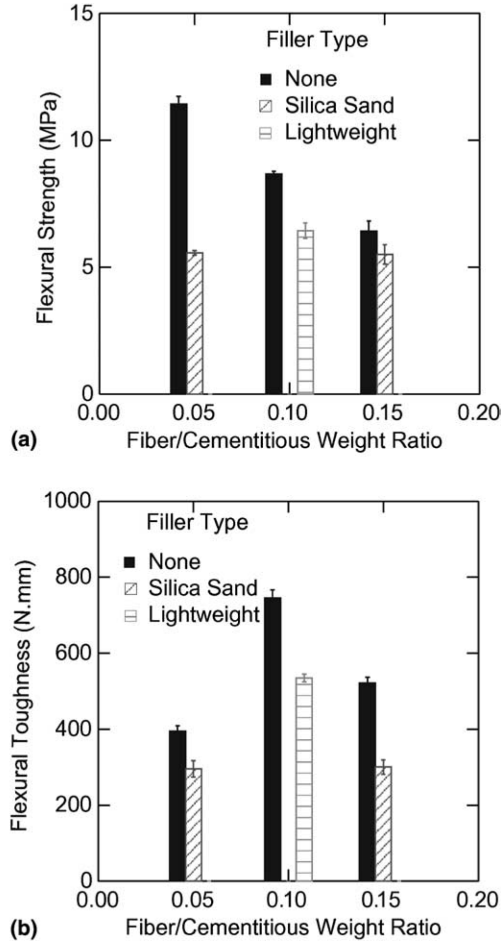

Fig. 11. Effects of light-weight and normal-weight fillers on flexural performance of extruded fiber cement in saturated condition (means and standard errors). (a) Flexural strength and (b) flexural toughness.

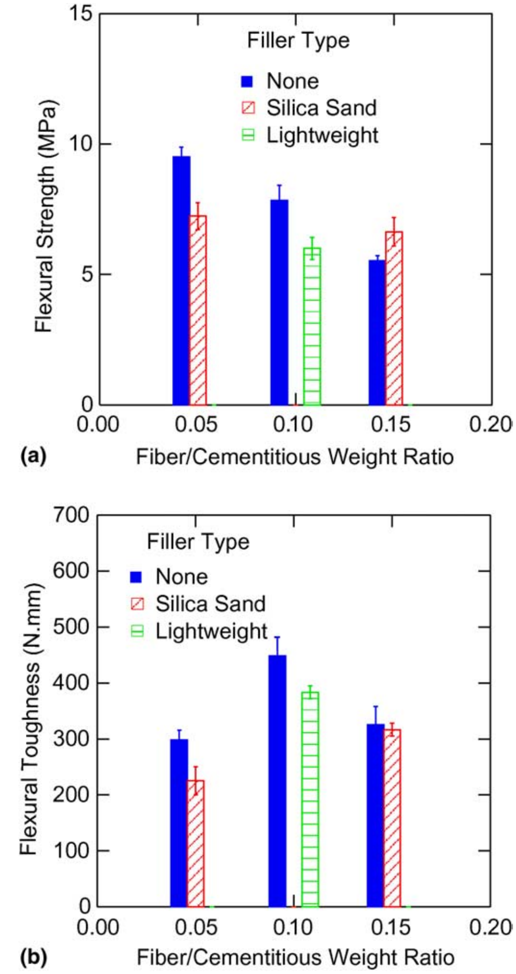

Fig. 12. Effects of light-weight and normal-weight fillers on flexural performance of extruded softwood fiber cement after freeze-thaw exposure (means and standard errors). (a) Flexural strength and (b) flexural toughness.

45% and 54% in average, respectively in case of softwood fibers. Silica sand fillers decreased flexural toughness by 31% and 40% in average, in case of hardwood and recycled fibers, respectively. Saturation of wood fiber cement products produce reversible changes in (hydrogen) bonds between wood fibers which lower the flexural strength of wood fiber cement products; by encouraging fiber pull-out against the frictional resistance of saturated (swollen) wood fibers against cementitious matrix, saturation enhances the ductility (deformation capacity) of wood fiber cement products. Comparison of the flexural performance of extruded softwood fiber cement products in saturated condition (Fig. 11) and in air-dried condition (Fig. 8) suggests that fillers reduce moisture-sensitivity of extruded wood fiber cement products.

Figs. 12–14 present flexural performance characteristics of extruded softwood fiber cement products after exposure to freeze-thaw cycles, wet–dry cycles and extended immersion in warm water, respectively. The unaged flexural performance data were presented in Fig. 8. A comparison of aged (Figs. 12–14) versus unaged (Fig. 8) performance characteristics indicates that fillers generally enhance the durability characteristics of extruded wood fiber cement products. The gains in durability with the introduction of fillers is more pronounced at higher fiber contents (10% and 15% fiber/cementitious ratios). This may be attributed to the fact that increasing the filler content leads to reducing voids content, hence, permeability may be decreased which reflects on durability characteristics.

The nailability of extruded wood fiber cement products was assessed in air-dried condition, with a ranking of "one" indicating excellent nailability and "zero" indicating very poor nailability. Nailability is observed to be improved with increasing fiber content. Normal-weight filler (silica sand) adversely influences nailability of extruded wood fiber cement products. There is not sufficient data to judge the effect of light-weight aggregates on nailability; there seems to be the potential for

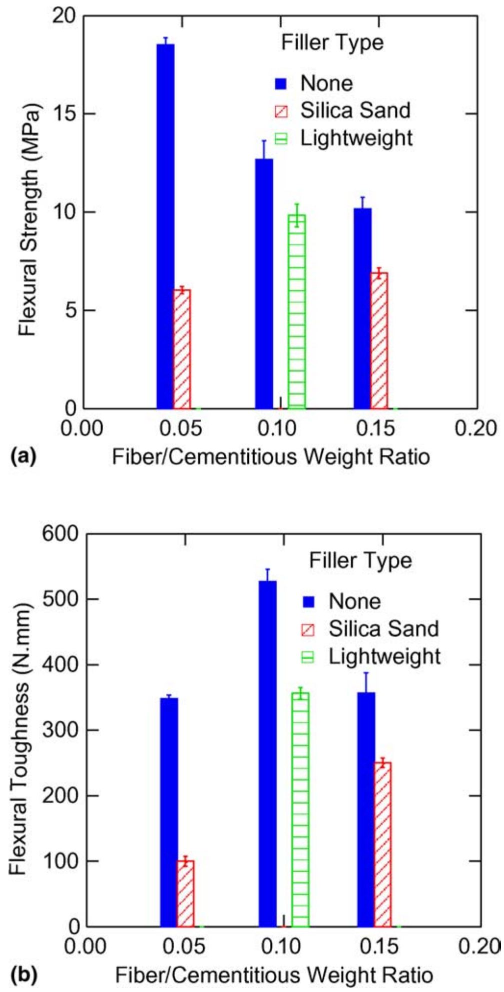

Fig. 13. Effects of light-weight and normal-weight fillers on flexural performance of extruded softwood fiber cement after wet–dry exposure (means and standard errors). (a) Flexural strength and (b) flexural toughness.

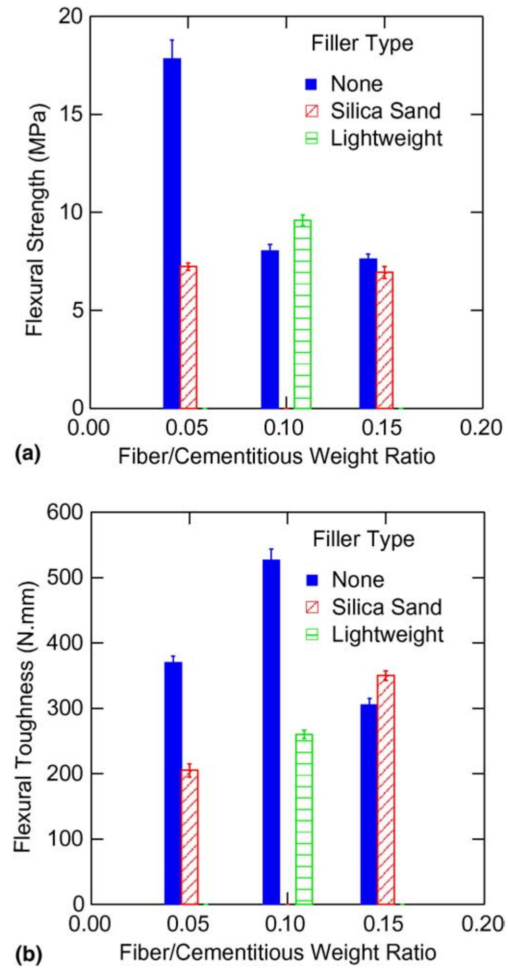

Fig. 14. Effects of light-weight and normal-weight fillers on flexural performance of extruded softwood fiber cement after extended warm water immersion (means and standard errors). (a) Flexural strength and (b) flexural toughness.

light-weight aggregates to actually improve the nailability of extruded wood fiber cement products; this is due to the lower modulus of elasticity of light-weight aggregates that lead to reduction in the rigidity of cement products.

4. Summary and conclusions

The effects of normal-weight and light-weight filler on various aspects of extruded wood fiber cement products incorporating softwood, hardwood, and recycled fibers were investigated. Two types of filler (silica sand and light-weight aggregate) were used in this investigation. The light-weight aggregate was expanded shale with specific gravity of 1.19 and average particle size of about 50 μm; the silica sand had an average particle size close to 150 μm. Silica sand and light-weight aggregates were added to the matrix at 25% and 1.1%, respectively, by weight of cementitious materials (cement plus silica fume). At these dosages, fillers had relatively small effects on the bulk specific gravity of extruded wood fiber cement products. Silica sand produced some reduction in water absorption capacity of boards. Both fillers generally reduced the flexural strength and toughness of extruded wood fiber cement products due to their low modulus of elasticity. Fillers, however, reduced moisture-sensitivity of wood fiber cement products due to their fineness and tendency to block small pores. The adverse effects of moisture on flexural performance were less pronounced in the presence of fillers. Accelerated aging tests involving repeated freeze-thaw and wet–dry cycles and also extended immersion in warm water indicated that extruded wood fiber cement products incorporating fillers provide enhanced durability characteristics. Normal-weight fillers lowered the nailability of extruded wood fiber cement products; there is reason to believe that light-weight fillers could potentially improve nailability of the products.

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