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Microstructure of extruded cement-bonded fiberboard

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Abstract

The microstructure of cement-bonded fiberboard manufactured by extrusion process was studied using scanning electron microscope (SEM). Comparison between extruded and cast fiberboard revealed that the extruded products 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. The dominant component in extruded fiberboard was the type of fiber. Extrusion was capable of incorporating both hydrophilic and hydrophobic fibers into fiberboard production. It was found the sand content had significant effect on toughness. The more the sand added, the less the toughness. Fiber dispersion seemed not to be critical. Fiberboard made by nondispersive mixing exhibited satisfactory performance. Accordingly, the mixing time and energy in extrusion production could therefore be reduced.

Keywords: Microstructure; Cement fiberboard; Extrusion; Fiber reinforcement

1. Introduction

The past decade has seen an increase in prefabrication of cement-bonded fiberboard around world. Compared with conventional wood and other products, the cement fiberboard has higher fire resistance, moisture resistance, and better durability. Also, problems commonly related to wood like rot and insect attack are altogether eliminated. The current major applications for cement-bonded fiberboard when substituting products in residential usage are for lap and panel siding, and simulated cedar shake and shingle products. Other potential uses are for slate roofing and flat panel applications including underlayment, tile backer board, and lumber substitutes as trim, fascia, and corner boards.

In manufacturing the cement fiberboard, Hatschek processing has been commonly used with cellulose fibers to replace asbestos cement products [1–3]. Cellulose fibers are exclusively used because of their excellent water carrying capacity. The production was originally developed in Europe and later adopted for use in Australia and Japan, among other countries and regions of the world. Merging into the North America's market has just begun [4]. As more people move into single family housing, it is expected that a stable economy combined with an increased housing demand will provide an excellent place for cement fiberboard in the roofing and siding industry [4].

Extrusion is a traditional method of making clay bricks and concrete blocks [5]. Recently, the process has been reevaluated as an alternative to Hatschek process [6], because extrusion produces near zero pollution, enables the use of both hydrophilic and hydrophobic fibers with any types of fillers, and has a great capacity in making solid or hollow shapes. A number of successful applications included extruded pressure pipes [7], extruded cellulose fiberboard [8,9], and extruded exterior sidings [10].

Unlike the fiberboard manufactured by Hatschek process, the structure of extruded cement board has not been extensively studied. This article is to report a microscopic study on the quality of the extruded fiberboard and to show the flexibility of the technique to incorporate various fibers and fillers. Comparison was made between extruded and cast fiberboard to demonstrate the effect of processing on strength, toughness, fiber distribution, and porosity. A product development project was

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Table 1
Mechanical and physical properties of fibers

	Diameter (μm)	Length (mm)	Density (g/cc)	Strength (MPa)	Modulus (GPa)	Strain at failure (%)
PET	30	6	1.1	50–100	1.2–2	3
AR glass	14 (strand)	12	2.6	3600	70	2
PO	60	18	0.91	275	2.8	15
PVA	14	6	1.3	1400	36	6

followed to investigate the influence of material constituents and mixing procedure on the performance of the extruded products. The mechanical properties of fiberboard so made were evaluated by tensile or flexural tests, and the fiber dispersion, fiber orientation, porosity, fractured fiber morphology, and interaction of fibers with sand were examined under the scanning electron microscope (SEM).

2. Materials and sample preparation

2.1. Fibers

Four different types of fibers were experimented in this study for the extrusion production of cement fiberboard. These were polyethylene terephthalate (PET) fiber, alkali-resistant (AR) glass fiber, polyolefin (PO) fiber, and polyvinyl alcohol (PVA) fiber. The mechanical and physical properties of the fibers are listed in Table 1. Except for the PVA fibers, which are hydrophilic, all the other three show hydrophobicity. PET fibers are made from the recycled plastic beverage bottles. While AR glass fibers are bundled with 102 filaments in one strand, PET, PO, and PVA fibers are monofilament with different fiber lengths and diameters.

2.2. Sample preparation for comparison study

Table 2 shows the material compositions of extruded and cast fiberboard for comparison study. The two production methods used the same mix design except that methyl cellulose (MC), a viscosity modifier, was used in extrusion to achieve extrudable dough body. Since MC was not necessary for cast, it was replaced by the same amount of high-range water reducer (HRWR) to improve workability in casting. Type I cement was used with slurry silica fume. Only PVA fibers were experimented in the comparison study.

Table 2
Material compositions for comparison study (by weight)

	Batch	
	#1 (extruded)	#2 (cast)
Fiber type	PVA	PVA
Fiber ratio (% by volume)	2.2	2.2
W/C ratio	0.29	0.29
Silica fume-to-cement ratio	0.18	0.18
MC-to-cement ratio	0.01	0
HRWR-to-cement ratio	0.017	0.027

The extruded fiberboard was fabricated by a laboratory-type single-screw auger extruder [11]. The fibers were mixed with silica fume slurry first to sufficiently wet the fiber surface and then with other dry powders plus the required water. The premixed dough-like body was fed into the pugmill chamber, forwarded by the auger, compacted inside the die, and extruded out to form thin sheets of 76 mm wide and 6 mm thick. The cast fiberboard of a dimension of 76 mm wide, 12 mm thick, and 200 mm long was prepared by conventional casting. Since the fiber ratio was high and the water-to-cement ratio (W/C) low, the workability of casting was poor. Heavy vibration was therefore used to consolidate the samples.

2.3. Sample preparation for product development

A product development project was followed to investigate the feasibility of using extrusion technology to fabricate special building products. The material compositions of six mix designs for the project are shown in Table 3. They were quite different from Table 2. Fiber volume ratio was fixed at 3% with four different types (Table 1). The basic mix designs (Batches #3–6) employed Type I Portland cement with marble sand-to-cement ratio of 0.65, metakaolin-to-cement ratio of 0.2, styrene–butadiene (SB) latex (solid)-to-cement ratio of 0.14, and HRWR-to-cement ratio of 0.01. Metakaolin was chosen as the mineral additive because of its favorite white color. The liquid latex had several functions. It worked as a dispersant for fiber distribution, as a wetting agent for fibers to attain better bond with cement matrix, and as a waterproofing

Table 3
Material compositions for fiberboard development (by weight)

	Batch					
	#3	#4	#5	#6	#7	#8
Fiber type	PET	Glass	PO	PVA	PVA	PVA
Fiber ratio (% by volume)	3	3	3	3	3	3
W/C ratio	0.38	0.31	0.29	0.32	0.30	0.32
Metakaolin-to-cement ratio	0.2	0.2	0.2	0.2	0.2	0.2
MC-to-cement ratio	0.01	0.01	0.01	0.01	0.01	0.01
HRWR-to-cement ratio	0.01	0.01	0.01	0.01	0.01	0.01
SB latex-to-cement ratio	0.14	0.14	0.14	0.14	0.14	0.14
Marble sand-to-cement ratio	0.65	0.65	0.65	0.65	0.0	0.65
Mixing method	Disp.	Disp.	Disp.	Disp.	Disp.	Nondisp.

Disp. = dispersive mixing; Nondisp. = nondispersive mixing.

membrane to enhance the resistance of the final product to the water permeability. Marble sand was added to reduce the drying shrinkage potential as well as to achieve economic product. The particle size distribution of marble sand was obtained through sieve analysis. By a series of experiments, it was found that the combination of 75% of sand between 150 and 300 μm and 25% between 75 and 150 μm provided a better extrudability. The product had an easy flow inside the die, a smooth surface, and a straight edge without defect. Water was used to adjust the dough forming process. Therefore, W/C ratios were indicative of the influence of material constituents.

Compared to Batch #6, Batch #7 used no sand and Batch #8 had the same composition as Batch #6 except that mixing procedure was different. Batch #7 was intended to assess the effect of sand content on the strength and toughness and Batch #8 to study the mixing procedure. The typical mixing used in all batches except Batch #8 was called dispersive mixing, in which the fibers were first mixed with either silica fume slurry or liquid latex to get dispersed and coated and then with the dry components plus the required water and HRWR. The so-called nondispersive mixing method was experimented in Batch #8 to examine how incomplete dispersion of fibers might affect the performance. In nondispersive mixing, fibers were added at the very last stage after the dough was formed. The distribution of the fibers was achieved through the kneading of the dough with the fibers. The uniform dispersion was not expected. In this way, fibers underwent the least mixing action, and thus carried a minimum possible damage. It also required much less mixing time and energy.

3. Test procedure

3.1. Tensile tests

Uniaxial tension tests were conducted to compare the strength and toughness of the extruded and cast cement fiberboard (Batches #1 and #2). This is because extruded and cast samples had different thickness due to the difficulty in casting a fiberboard of 6 mm thick. Therefore, the uniaxial tension tests were used to minimize the size effect on the comparison. Tension coupons were cut from the fiberboard to have a specimen of 25.4 mm wide and 200 mm long. Tests were conducted using an MTS machine with a loading rate 0.025 mm/min. Samples were tested after 28 days of curing in a 100% relative humidity environment. For extruded samples, specimens were loaded in the extrusion direction. At least five samples were tested for one batch. The tensile strain was calculated by averaging displacement measured by two LVDT with a gage length of 76 mm. Tensile strength, Young's modulus, and toughness were directly obtained from the tensile tests. The toughness was defined as the area under the tensile stress–strain curve up to a cut-off tensile strain of 0.5% for comparison.

3.2. Flexural tests

The mechanical properties of extruded fiberboard (Batches #3–8) in the product development project were evaluated by a three-point bending test with a span of 101 mm. The specimen size was 150 mm long, 76 mm wide, and 6 mm thick. The 7-day tests were carried out in a displacement control mode at a loading rate of 0.04 mm/s. The specimens were cured in a moisture room for 6 days and dried in an environmental chamber with a 50% relative humidity for 1 day before testing. The drying process was to assist latex to form a solid film. At least five samples were tested for each batch.

3.3. Porosity measurement

D-drying method was used to measure and compare the porosity of fiberboard made by extrusion (Batch #1) and by casting (Batch #2). Two specimens from each were randomly selected. The size of the specimen was 25.4 × 12 × 6 mm^3. The specimens were first vacuumed in a desiccator for 2 h, and then immersed in de-aired water under the vacuum for two more hours. To obtain complete saturation, the specimens were left in the water without vacuum for another 24 h. The pores inside the saturated specimens were assumed to fill with water. Under the saturated surface dry condition, the specimens were weighed to obtain the initial mass and then left in another dessicator connected to the D-drying device. D-drying is defined as a drying process that dries the specimens at partial water vapor pressure of 0.07 Pa under vacuum condition at ambient temperature [12]. The subsequent weight loss was measured every 4 to 5 days until two consecutive measures had a same reading up to the second decimal point. The tests took 24 days to finish. The total weight loss represented the volume of pores that were initially occupied by the evaporable water. The porosity was defined as the ratio of the volume of pores to total volume.

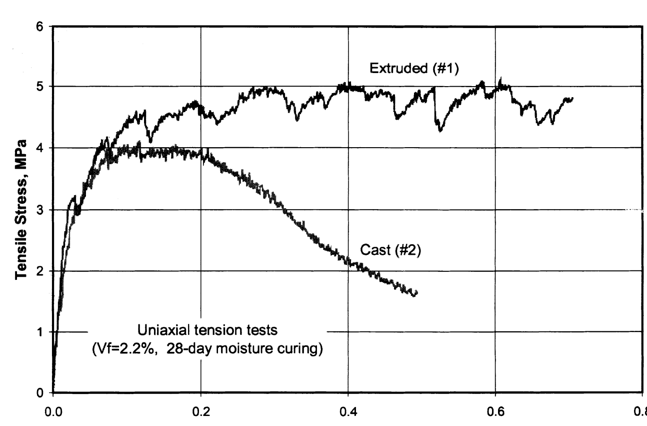

Fig. 1. Typical tensile stress–strain curves for extruded and cast fiberboard.

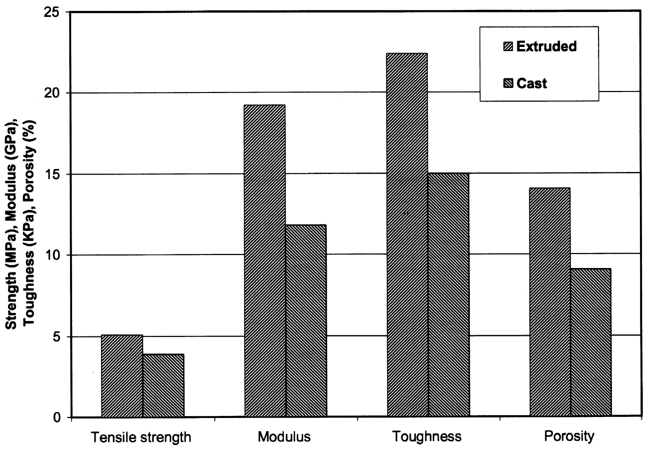

Fig. 2. Performance comparison between extruded and cast fiberboard.

3.4. Microscopic analysis

SEM was used to examine the fracture surface and the polished surface for fiber dispersion, fiber orientation, fractured fiber morphology, and process-induced porosity in fiberboard.

4. Comparison between extruded and cast fiberboards

4.1. Tensile response

The typical uniaxial tensile stress–strain curves for extruded and cast fiberboards are shown in Fig. 1. Fiber reinforcement alters significantly the nature of brittle material. The yielding type of behavior was observed for all the extruded fiberboards. The zigzag behavior for the extruded along its postpeak yielding reflected a loading–unloading process, which involved fiber bridging and sequential matrix cracking. In contrary, the conventionally cast fiberboard exhibited a postpeak softening accompanied by a narrow crack band. The averaged values of tensile strength, Young's modulus, and toughness for each batch are compared in Fig. 2. Extruded fiberboard exhibited higher tensile strength, stiffness, and toughness.

4.2. Fiber orientation and distribution

The fracture surfaces as well as the polished flat surfaces of the fiberboard were examined under SEM to study the effect of processing. Fiber orientations on

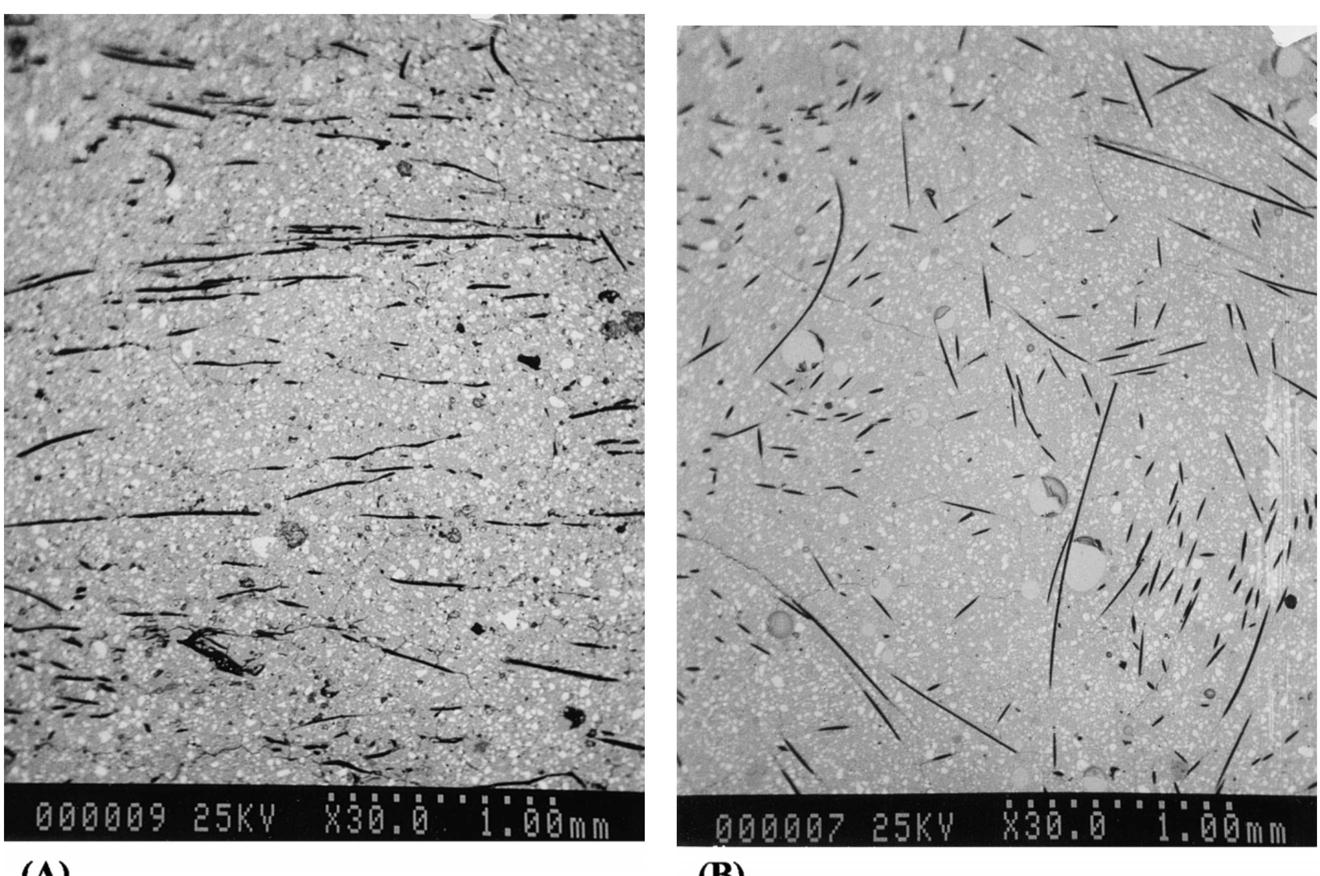

Fig. 3. Fiber orientation in cement fiberboard. (A) Extruded (Batch #1, the extrusion direction is horizontal) and (B) cast (Batch #2).

polished surface are shown in Fig. 3. For extruded fiberboard, the horizontal direction is the extrusion direction. Apparently, extrusion generated a fiber alignment pattern and no visible entrapped air voids were observed. On the other hand, the fibers in the cast fiberboard were randomly oriented and the air voids were evident. Fiber distribution was also influenced by the processing. Fig. 4 shows the SEM fractographs from the fracture surfaces. For extruded fiberboard, fibers were well dispersed with uniform fiber pullout (Fig. 4A). In the cast fiberboard, however, fibers were bundled (Fig. 4B). The dispersion of fibers in extruded fiberboard was likely attributed to kneading process during mixing. The conventional mixing was difficult to distribute the fibers at such a low water content and a high fiber ratio.

The bond of fiber with matrix was characterized by SEM view of pullout fiber on fracture surface at a larger magnification. The fractured fibers from extruded board had shown a rougher surface with filaments peeled off and core pulled out (Fig. 5A). This was an indication of ductile fracture with high energy-dissipation capacity. The same phenomenon was not evident in Fig. 5B, where the fractured fibers were of cleavage type, and the fiber

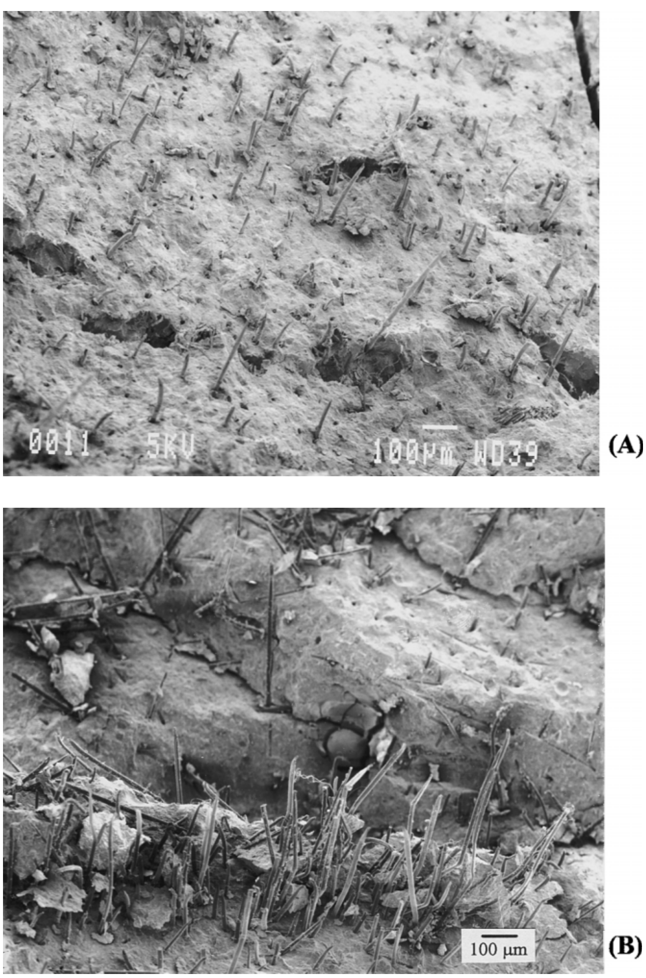

Fig. 4. Fiber distribution in cement fiberboard. (A) Extruded (Batch #1) and (B) cast (Batch #2).

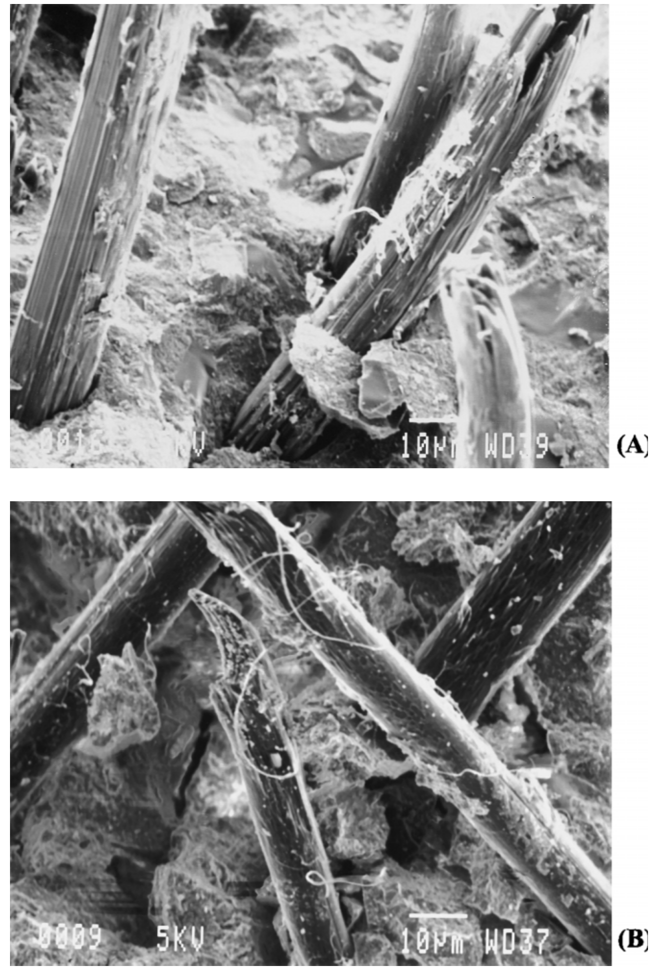

Fig. 5. Pullout fibers on fracture surface of fiberboard. (A) Extruded (Batch #1) and (B) cast (Batch #2).

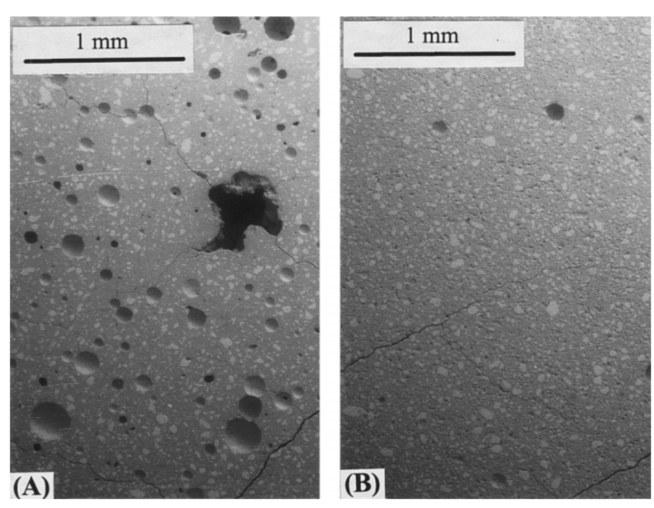

Fig. 6. Effect of MC on air void structure in cast cement paste. (A) Paste with 1% MC and (B) paste without MC.

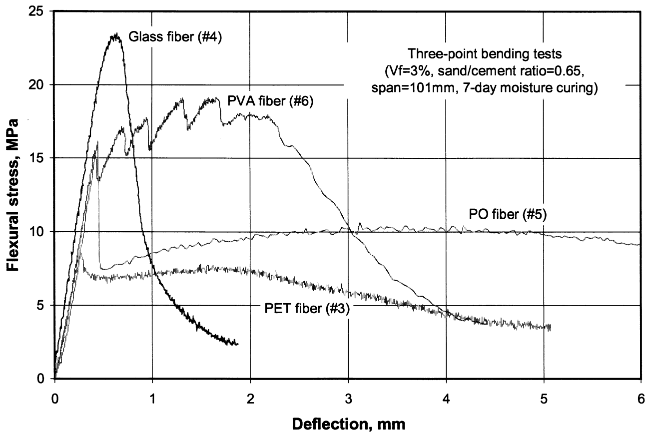

Fig. 7. Typical flexural stress–deflection curves of extruded fiberboard with different fibers.

surface was relatively smooth, suggesting a poorer bond with matrix.

4.3. Porosity

A close look on fracture surface of extruded fiberboard in Fig. 4A revealed a number of air voids that were distributed, disconnected, and of a size in the range of 100–200 μm. It was not seen in cast fiberboard as shown in Fig. 4B, although the fibers were not uniformly distributed. This observation subsequently led to a porosity measurement by D-drying method. The comparison is also plotted in Fig. 2. The extruded fiberboard did have a porosity 55% higher than the cast one.

The cause of the high porosity in extruded fiberboard is likely related to the MC used. MC modifies the cement-based mix to an extrudable dough-body. At the same time, it also plays a role as an air-entraining agent by generating a foam structure in the material. To show this effect, two cement pastes (no fibers) of the same composition as used in Batch #2 were cast into thin sheets of 12 mm thick, one with 1% MC and the other without. After 7 days curing, the

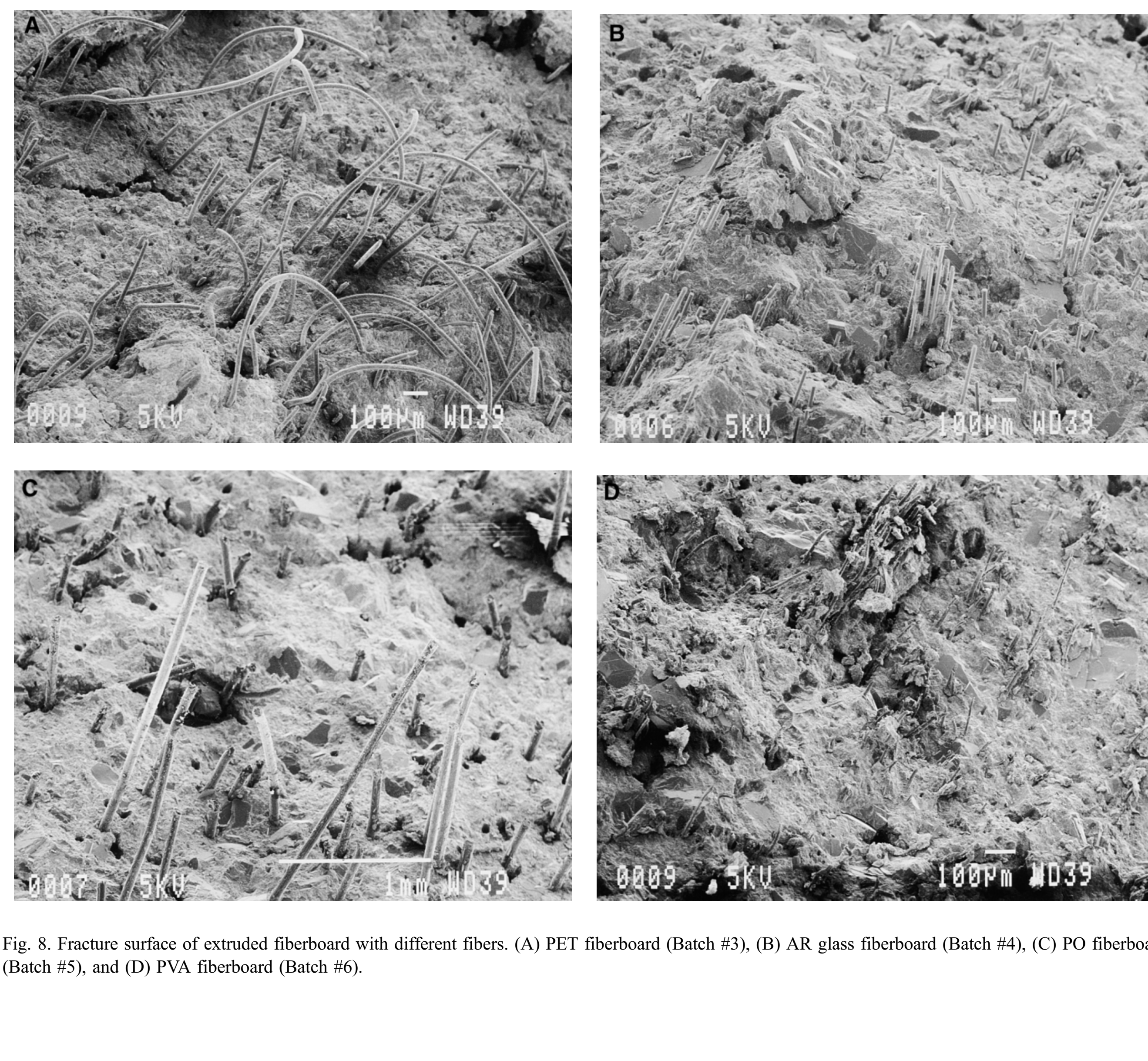

Fig. 8. Fracture surface of extruded fiberboard with different fibers. (A) PET fiberboard (Batch #3), (B) AR glass fiberboard (Batch #4), (C) PO fiberboard (Batch #5), and (D) PVA fiberboard (Batch #6).

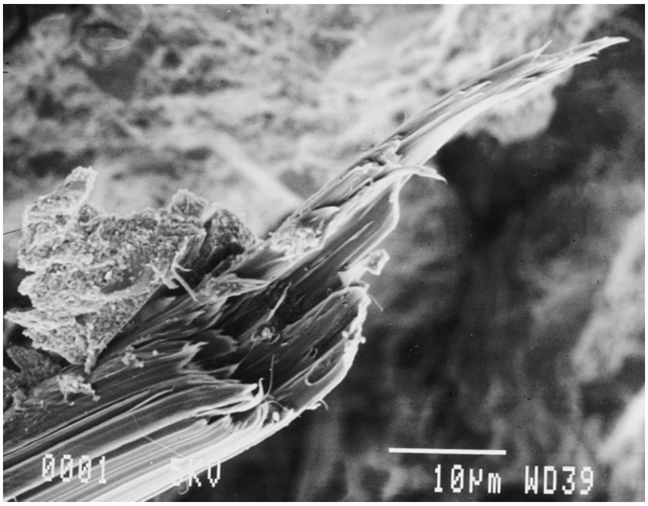

Fig. 9. Filament peel-off and core pullout of a fiber in PVA fiberboard (Batch #6).

polished pastes were observed under secondary mode SEM and the typical micrographs are presented in Fig. 6. The MC modification did introduce quite a number of circular air voids (Fig. 6A), which were distributed and disconnected with maximum diameter of about 250 μm. The structure of air voids introduced by MC was similar to that intentionally entrained in concrete by air entraining agent for freeze–thaw resistance. As a comparison, the paste without MC showed only a few entrapped air voids from mixing and placing (Fig. 6B). Even with a high percent air voids, the extruded fiberboard still demonstrated a higher strength. This was likely attributed to the fiber alignment, fiber distribution, and the better bond of fiber with matrix in the presence of MC.

5. Development of extruded fiberboard

5.1. Effect of fiber types

Fig. 7 shows the typical flexural stress–deflection curves of fiberboard made of four different fibers, hydrophilic PVA fibers, hydrophobic PET, PO, and glass fibers. The marble sand was used at a sand-to-cement ratio of 0.65. To keep the consistent viscosity of an extrudable mix, W/C ratio was adjusted accordingly in a narrow range (Table 3). The glass fiberboard had the highest strength, followed by PVA, PO, and PET. Although PVA fibers were five times stronger than PO fibers, their first crack strengths were approximately the same. The toughness of the material was represented by the postpeak response. The glass fiberboard exhibited a strain-softening behavior, while as the PVA fiberboard a postpeak hardening. Both PO and PET boards underwent sudden load drop, but maintained a large postpeak deflection. SEM view of the fracture surface for each fiberboard is shown in Fig. 8. Both PET and PO fibers had smooth fiber surface, indicating a weak bond of fiber with matrix (Fig. 8A and C). Since PET fibers were shorter in length and smaller in diameter, there were more fibers in PET fiberboard than in PO board. The large postpeak deflections in both PET and PO fiberboard were apparently owing to the substantial fiber pullout after the first cracking. PO fibers exhibited the longest pullout length because of their initial long fiber length. A brittle-type fracture was observed in glass fiberboard with dispersed but smooth fibers and small pullout length (Fig. 8B). Dispersion of PVA fibers was not as uniform as seen in other fiberboard probably due to the small diameter of fibers and the hydrophilic surface (Fig. 8D). The pullout length was short, indicating that fiber pullout was not the dominating mechanism for toughness in PVA fiberboard. Instead, the strong bond between fibers and matrix contributed dramatically to the strength and toughness. A close-up view of the fractured fiber is shown in Fig. 9. The fiber had a hollow tip and a core pulled out. The grooved surface manifested typical filament peel-off. The other mechanism was possibly the splitting of fiber as seen in Fig. 10. A single fiber with a diameter of 14 μm was split into a bundle of submicron monofilament during the postpeak multiple cracking. The process of fiber stretching, splitting, fracture, and pullout implies an excellent bond of fiber with matrix and a superior energy absorption capacity of the PVA fiberboard.

5.2. Effect of sand content

The effect of sand content on strength and toughness of PVA fiberboard was studied by comparing Batch #6 with Batch #7, which used no sand. The typical flexural stress and deflection curves are plotted in Fig. 11. It was obvious that the addition of the sand substantially reduced peak load and ductility, although the first crack strength was not

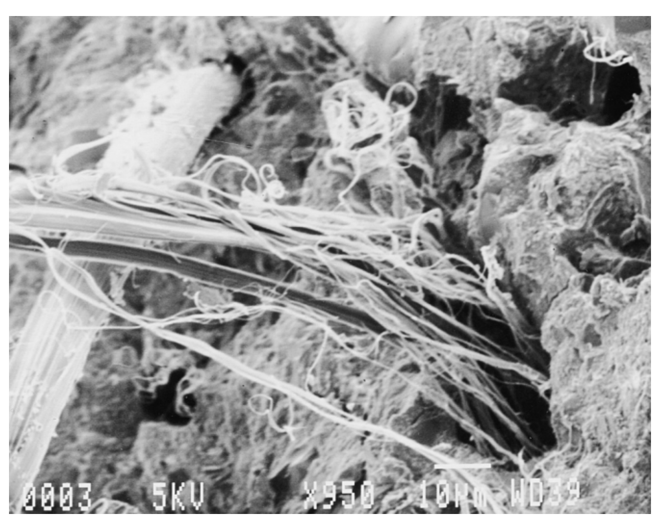

Fig. 10. Splitting of fiber in PVA fiberboard (Batch #6).

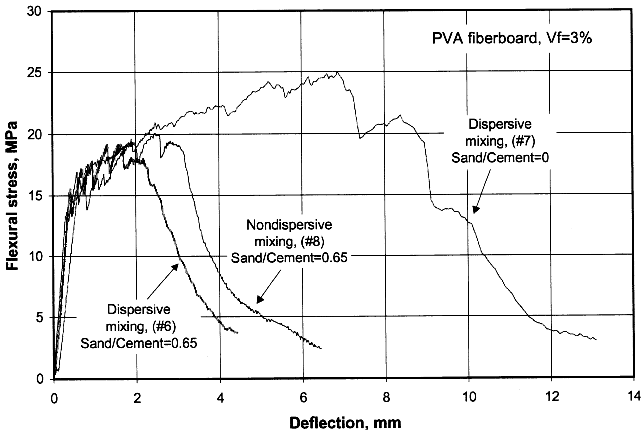

Fig. 11. Effect of sand content and mixing procedure on the performance of PVA fiberboard.

affected at all. This was indicative of a weak bond of fiber with matrix in the presence of the sand. The interaction of PVA fibers with sand grains was examined by SEM. Fig. 12 represents the typical picture. Compared to the size of sand grain, the diameter of the fiber was very small. The angular sand grains were likely to cut the fibers during the fracture process, leading to a reduction of strength and ductility. In addition, more sand added was always meant less cement binder and thus weaker bond of fiber to matrix. Fiber dispersion was also influenced by the addition of the sand. Since sand grains were much larger than the fibers, it was difficult to achieve similar distribution of fibers as observed in paste matrix (Fig. 4A). This could again decrease the efficiency of fiber reinforcement.

5.3. *Effect of mixing methods*

Nondispersive mixing was attempted in Batch #8 to minimize the mixing time and energy, and to keep the integrity of the fibers as much as possible. Compared to Batch #6 in Fig. 11, fiberboard made by nondispersive mixing (Batch #8) had a slightly higher strength and ductility. This phenomenon was also observed in glass fiberboard as well. Since fibers were added after the dough was formed, bundles of fibers were expected. The SEM view of fiber distribution in nondispersively made fiberboard is shown in Fig. 13. Fiber distribution was not uniform. However, it was comparable to that made by dispersive method as seen in Fig. 8D. The nondispersive approach provided an alternative to the mixing and showed, even if the fibers were not well dispersed, the fiberboard so made could still perform satisfactorily.

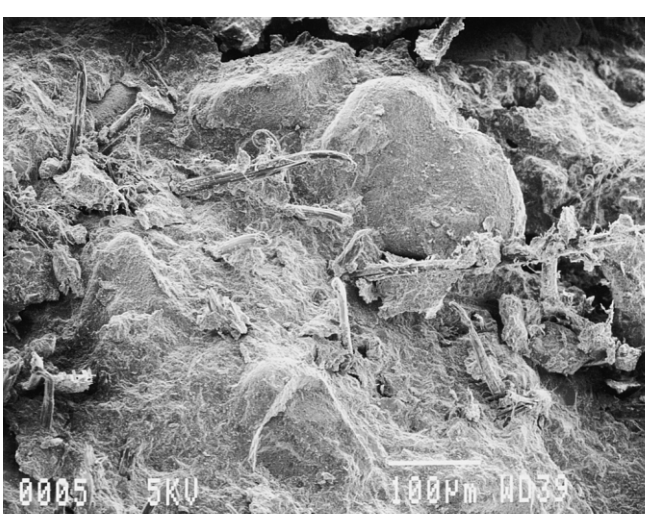

Fig. 12. Interaction of fibers with sand grains in PVA fiberboard (Batch #6).

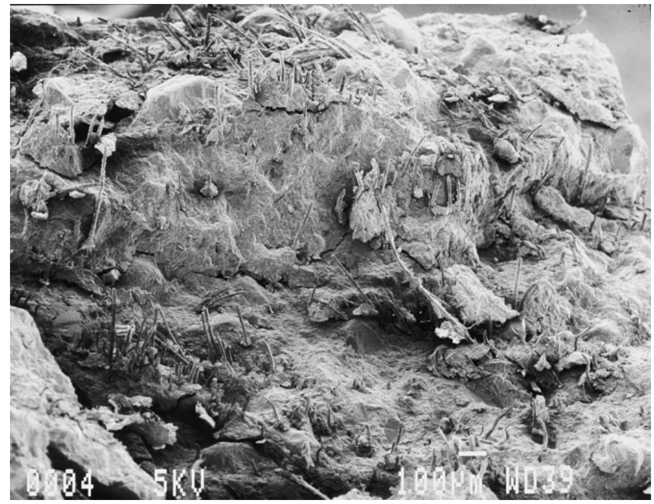

Fig. 13. Fiber distribution in PVA fiberboard made by nondispersive mixing.

6. Conclusions

Results of this study demonstrate that the processing can alter substantially the performance of the cement fiberboard. Compared to the conventional casting, extrusion can produce a board having better strength, stiffness, toughness, fiber distribution, and bond, even though the extruded products exhibit high percent air voids. The effect of the entrained air voids by the process aid needs further investigation. The distributed and disconnected air voids might be beneficial to the durability of the fiberboard.

The type of fiber used determines the performance of extruded fiberboard. Extrusion has proven an effective approach to make cement board with almost any type of fiber and any filler for matrix, providing a wide range to trade off the performance and the cost. The addition of the sand reduces the strength and ductility owing to coarser matrix and less binder. Nondispersive mixing method by adding fiber in the very last can produce a fiberboard with slightly increased strength and ductility. This efficient approach is expected to save time and energy in mass production.

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