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Properties of PVA-reinforced cement-bonded fiberboards processed with calender extrusion

Abstract: This research investigates the application of calender extrusion as a novel technique in the production of cement fiberboards. The technique is successfully used in the production of non-structural building elements. The properties of the produced composites are discussed in this paper, particularly with regards the polyvinyl alcohol (PVA) fiber used in the study. The research involves an experiment to examine the mechanical properties and microstructure of the composites, and the results indicate that calender extrusion is a promising method for the production of thin and wide cement composites. These products can be shaped into various three-dimensional forms in the green state after processing. Based on the results, the mechanical properties of cement-bonded fiberboards vary with processing direction due to the alignment of fibers. Fiber content is the most significant factor with regards the tensile and flexural properties of fiber-reinforced cementitious products processed with calender extrusion. Moreover, processed composites have adequate screw head pull-through and freeze-thaw resistance.

Keywords: cement; composite materials; fiberboard; fiber-reinforced cement board; poly(vinyl alcohol).

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1 Introduction

The use of cement composites to clad structures such as high-rise buildings is widespread among architects [1]. Engineers prefer to use thin cement-based composite elements to reduce the loads on building facades, because thin panels lower the self-weight of buildings, thus reducing the loads buildings may experience during an earthquake.

Many production techniques result in products with a wide range of material properties. On the one hand, conventional cement composite processing techniques, such as casting and spraying, are either expensive or very slow compared with cement-bonded fiberboard panel production techniques. On the other hand, the technical properties of the cement composites produced with conventional methods are significantly better than those of cement-bonded fiberboards that are produced using various mass production techniques.

The processing method plays a significant role in production speed and costs of cement-based composites. Considering their high volume of usage, finding efficient mass production techniques for fiberboards has gained importance in the building materials industry. The most widely used technique, the Hatschek process, was developed in the early 1900s for the production of flat and corrugated cement-based panels for cladding and roofing. In the Hatschek process, the dewatering slurry of fiber, cement, and water forms thin laminated layers. These layers are then bonded together while they are still in the plastic stage. This laminar structure has comparatively low strength and durability [2]. Asbestos, once the most popular fiber used in this method [3–6] has been replaced by alternative fibers, such as acrylic, glass, polyvinyl alcohol (PVA), polypropylene (PP), refined cellulose and sisal pulp [3, 6–9], in recent years due to the carcinogenic effects of asbestos [10]. PP, PVA, refined cellulose, or hybrids of these fibers have various effects on the strength and fracture toughness of cement-bonded fiberboard composites. PVA fibers became popular due to better bonding with cement matrix owing to its hydrophilic structure [11]. In addition to its usage as fiber, film products of PVA have also been used for many years [12]. The PVA production process has two main steps. First, the polymerization of vinyl acetate is carried out to produce poly(vinyl acetate) (PVAc); then, poly(vinyl alcohol) PVA is produced through the hydrolysis of poly(vinyl acetate) to PVA [13, 14].

Due to problems with durability and the mechanical performance of Hatschek products, alternative production techniques are being investigated to come up with thin-walled cement composites. Among these techniques, the preferred emerging alternative is the extrusion method. Extrusion is recommended as a highly efficient method for the production of short fiber-reinforced cementitious composites (SFRCCs). This process also improves the mechanical properties of cement-based materials [15–19]. In the extrusion process, stiff dough is passed through a die and shaped with a desired cross-section [2, 20, 21].

Extrusion has also been proposed as a suitable method for industrial production because it is a continuous process. In addition, it is more efficient to manufacture products with complicated shapes, such as hollow tubes, using this method [20–22]. Given that the wall of the extrusion die is effective in generating slip resistance against the extrusion direction, this method is used for relatively thicker products than Hatchek products. A slip process at the wall of a capillary dominates the paste flow of fresh SFRCCs during extrusion [23]. In practice, the product width is limited to 40 cm due to the dimensions of the extruder die. In order to achieve successful extrusion, the mixture must have optimum rheological properties, must be made of plastic so that it can properly be taken from the die, and must be stiff enough to hold its shape after extrusion. Excessive extrusion pressure is required if the die cross-section is too narrow. In addition, processing becomes very difficult due to wall slip resistance. For example, it is extremely difficult to extrude stiff paste from a die with a cross-section of 3 mm×1000 mm in order to produce a panel with dimensions of 1000 mm×3000 mm×3 mm. Moreover, the production is limited to thin and short fibers.

Hence, a novel processing technique that allows for continuous, rapid, and economical production of cement-bonded high-performance fiberboards is needed. Deficiencies in current fiberboard production techniques include durability problems related to laminated structure and dimensional instability due to environmental impacts. The laminated structure of products can be avoided in the extrusion technique. Given that excessive processing pressures are generated during conventional extrusion, the development of a novel method for the production of high-performance fiberboards is desirable.

This study describes the application of a novel processing method, called calender extrusion, for fiber-reinforced cement-based composites. This experimental study also investigates the mechanical properties and microstructure of the composites produced with this method. The basic principle of this method involves the calendering of dough-like cement composite mortar to the desired thickness in only a few steps. The most influential advantage of the method is that it achieves a production line with small cylinders (10–15 cm in diameter) and very low pressure without a dewatering process due to the improved plasticity of the dough-like material. The goals are to obtain a non-laminated structure of cement composite and to achieve mass production of the panels using a continuous and short production band with low labor costs.

The objective of the experimental study is to apply calender extrusion as a production method for cement-bonded fiberboards, thus creating a mix design that will work in the process. Here, the primary objective is the production of various non-structural architectural elements in the pilot scale system. These produced elements should have adequate strength and durability for use in external environment. The mechanical properties and microstructure of the produced composites are also investigated in the experimental study.

2 Materials and methods

2.1 Calender extrusion process

Calender extrusion is a process that is widely used in the production of plastic sheets. This technology has been adapted to cement-based materials to produce fiber-reinforced cement composite panels. Figure 1 shows the section schematic representation of the system. First, the dry substances, except the fibers, were weighed according to a proper mix design and poured into a mixer. Next, the dry mix was prepared. Here, half of the total amount of water to be introduced into the mix was added to moisten the mix. The mixture was thoroughly mixed for 5 min. Meanwhile, the plasticizer, liquid materials, other chemical additives, and the remaining portion of water, were mixed in a dosing unit and then added to the mixer. Finally, the fibers were added to the mix.

A feeding unit was used to drop the fresh state material to a pouring band. An auger squeezed the material through a die. The first band took the fiber included in the fresh mortar from the feeding unit and delivered it to the first roller set, which then compressed the cementitious mortar to a thickness of 3–5 cm. The material was then passed to a second band, which transferred the material to a second roller set. The thickness of the material was further decreased in the second roller set to 1–3 cm. The thinned material was taken from the rollers and passed to a third band, which transferred the material to a third roller set. The third and the fourth roller sets decreased the fresh material thickness to 0.6–1.0 cm and 0.2–0.4 cm, respectively. In order to successfully accomplish the calender extrusion process, very small cylinders with a 10-cm diameter were used. The distance between cylinders was maintained at 100 cm. The velocity of the production band was 200 cm/min.

An experimental study in the laboratory tested the proposed system and identified the properties of the cement-bonded fiberboard composites. In the laboratory study, a pilot scale calender set was used to produce thin fiberboard panel cement composites. Panels with thicknesses of 0.3

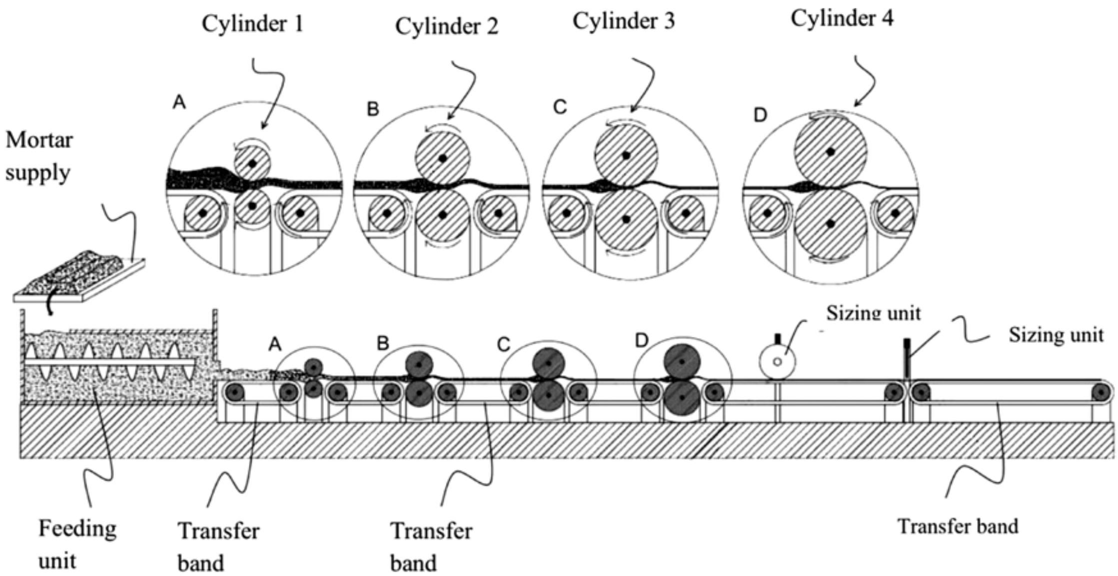


Figure 1 Schematic description of calender extrusion-section.

and 1.2 cm, which were produced with a pilot scale calendering system, were successfully produced in three steps.

2.2 Materials, mix properties, and sample preparation

The cement composite (Akcansa, Istanbul, Turkey) consisted of PVA fiber, cement, sand (Ege Region of Turkey), quartz dust (Ege Region of Turkey), superplasticizer (BASF, Istanbul, Turkey), and a synthetic polymer-based water-retaining agent. The experiment employed RSC 15-type PVA fibers with a length of 8 mm and diameter of 40 μm. Kuraray Co. Ltd. (Tokyo, Japan) supplied the fibers. Based on the manufacturer's declaration, the tensile strength and modulus of elasticity of the fibers were 1.4 and 35 GPa, respectively.

One cubic meter matrix contained 665 kg of CEMI 42.5, 445 kg of siliceous quartz dust, and 360 kg of siliceous sand. The maximum size of sand was 400 μm and that of quartz dust was 100 μm. The specific gravities of cement and siliceous materials were 3.16 and 2.64 g/cm^3, respectively.

The experimental study commenced with preliminary work to obtain the optimum mix proportions for calender extrusion (Istanbul, Turkey). The given proportions of dry materials helped keep the complete structure undamaged during the calendering process. The cement amount was limited and siliceous dust was used to avoid possible high shrinkage effects, such as curling, during drying. The water-to-cement ratio was initially set at 0.50 and then decreased gradually. The superplasticizer ratio was gradually increased from 1.0% of cement by weight. The optimum ratio was determined to be 0.41 of water to cement and 1.8% superplasticizer. A water-retaining cohesion-enhancing agent was used with the ratio of 0.8% of cement by weight. Surface quality and unity of the fresh calendered cement composite served as the main parameters for selecting optimum mix ratios. The study used different volumetric ratios of PVA fibers at 1.2% and 1.6%. After preparing each mixture, fresh mixes were processed using a pilot scale calendering machine.

2.3 Produced elements

Cement-bonded fiberboard composite panels were produced to conduct the laboratory work. In addition to panel-shaped samples, fresh-calendered cement-based composites were formed in different shapes to evaluate various shapes. These products were three-dimensional (3D) building elements. The thickness of the composite in these product forms varied depending on the product shape and dimension. Figure 2 shows a flat sheet with various dimensions. Figure 2A shows the cement composite sheet with dimensions of 60 cm×150 cm and a thickness of 3 mm. The weight of this sample was 4.8 kg. Figure 2B shows a 120 cm×280 cm panel, with a thickness of 12 mm. Hardening of the material allowed convenient handling, transporting, and fixing with screws or nails using carpenter tools. Figure 3A shows the panel screwed to steel studs at the laboratory. Figure 3B shows the rear side of the cement composite connected to metal brackets. The goal was to determine the connection ability of screws

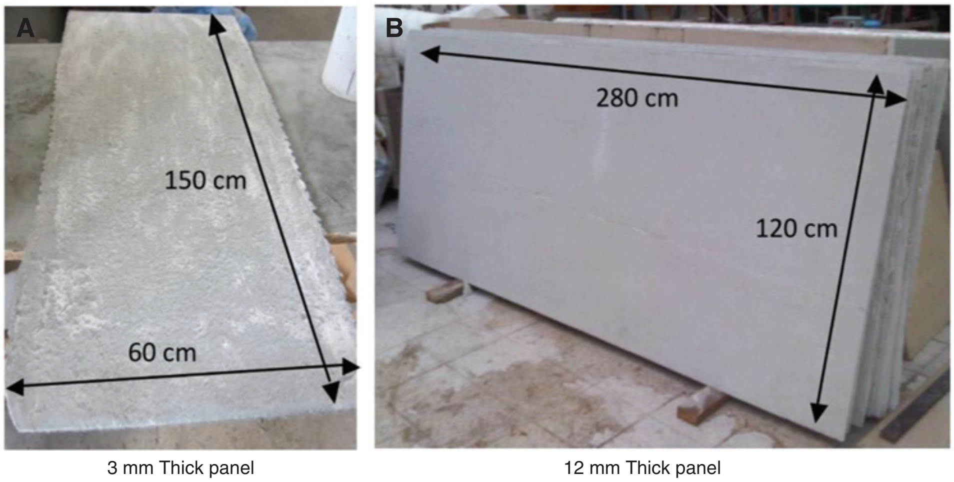


Figure 2 Calender extrusion cement-bonded fiberboards.

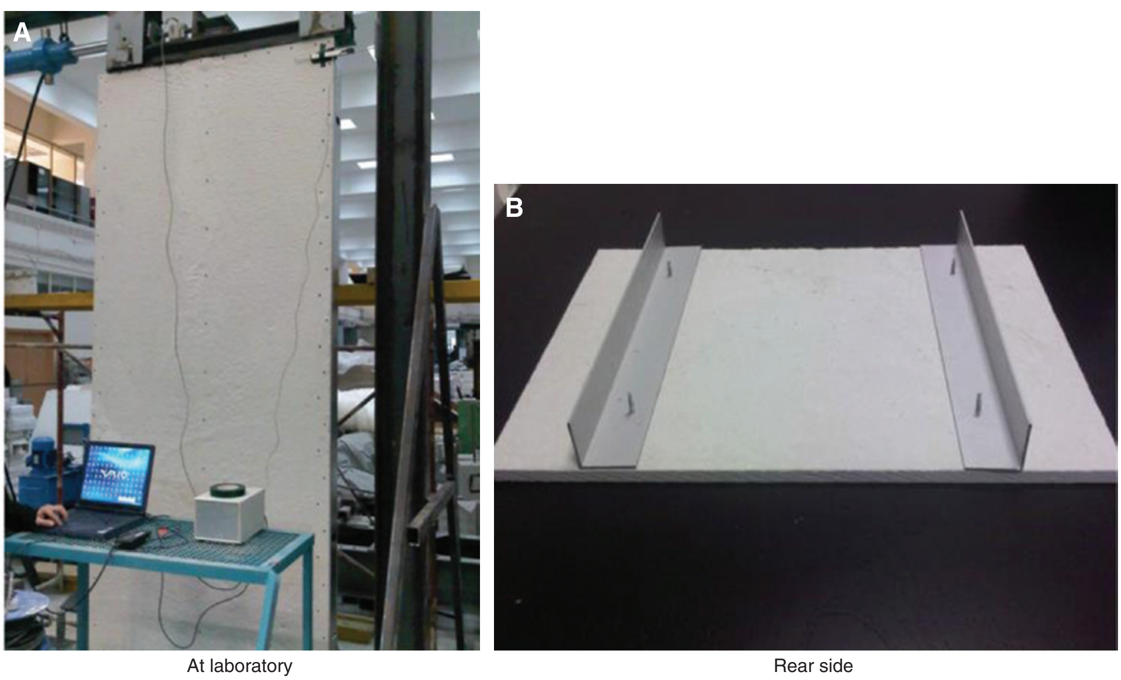


Figure 3 Screwed panel.

after hardening. The thickness of the panel was 12 mm. The system successfully carried its own weight. Moreover, screw head pull-through tests, carried out in accordance With ASTM D1037-12, quantified the connection ability [24]. The results are presented in the results section.

2.4 Tests performed

All samples were cured under laboratory conditions of 20°C temperature and 65% relative humidity. The curing time was 28 days. One day before the tests started, the panel samples were cut into 5 cm×35 cm pieces using a diamond saw for use in the flexural and tensile tests. The samples were taken from two directions on the tested panel. The first direction was longitudinal, parallel to the processing direction. These samples were coded as B. The second direction was transverse, perpendicular to the processing direction. These samples were coded as A. The locations of the samples taken from the longitudinal and transverse directions of the panel are shown in Figure 4.

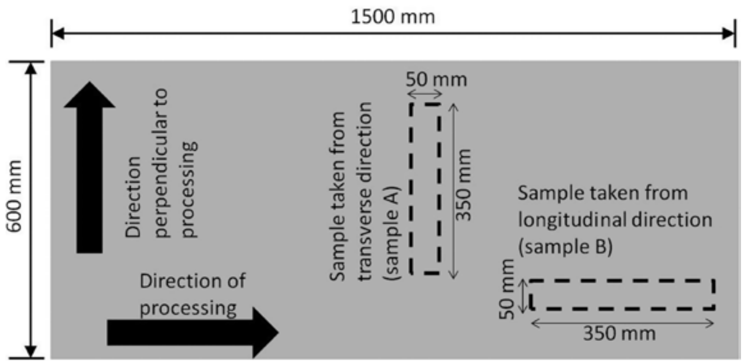


Figure 4 Schematic description of panel sampling.

The rheological properties of the mixture should be satisfactory in order to avoid future defects, such as lamination or surface tear. These defects formed in green state can lead to mechanical strength loss or an unpleasant aesthetic view. Visual inspections were made during production, and green strength tests were conducted. The thickness of the panels was measured at 10 points along the cross-section to determine the stability of the thickness. Freeze-thaw cycles according to ASTM C1185-08, microstructural observations, and mechanical strength tests were conducted on the samples taken from 3 mm-thick panels [25]. Compressive, flexural, and tensile strength tests were conducted on composites. The flexural properties of the PVA fiber-reinforced cement-based composite samples were determined using simple beam four-point loading, where the span length was selected as 300 mm. A closed-loop testing machine, the Instron 5500R (Instron, MA, USA), was used for the flexural tests. The crosshead rate was 1 mm/min. An MTS Criterion C43 504E (MTS, MN, USA) deformation-controlled testing machine with a capacity of 5 kN was used for the tensile strength tests. The elongation rate was maintained at 0.6 mm/s. After undergoing tensile and flexural testing, the samples were dried at 65°C. They were then coated with gold for microstructural observations with a scanning electron microscope (SEM).

3 Results and discussion

Visual inspections during production show a plastic behavior of the processed material in the green state. The material can be shaped into any form without any cracks or visual defects. Green strength values are also obtained as 4.0 and 4.9 kPa for the mixtures with fiber ratios of 1.2% and 1.6%, respectively, on 70 mm cube specimens. The unit weight of the composite increases from 1.35 to 1.79 kg/dm^3 during the panel production as the fresh composite is released through the cylinders.

The average thickness of the panel is 3.01 mm, while the maximum, minimum, and standard deviations are 3.05, 2.94 and 0.04 mm, respectively. Average unit weight of the composite is measured as 1.79 kg/dm^3, which indicates a denser structure than that of Hatschek fiberboard products, with a unit weight of 1.45 kg/dm^3. Average compressive strengths of the composites are recorded at 35.1 and 38.3 MPa for fiber contents of 1.2% and 1.6%, respectively. The average value of screw head pull-through test results is 5350 N, while the maximum, minimum, and standard deviation values are obtained as 5604, 5030 and 320 N, respectively. In addition, sampled subjected to accelerated freeze-thaw tests show no noticeable deterioration of the exposed surfaces following 100 freeze-thaw cycles.

Figures 5 and 6 show the longitudinal and transverse sample flexural behavior results, respectively. The relationships between the load and the corresponding deflections at mid-span are given in these figures. The samples taken in two different directions demonstrate significantly

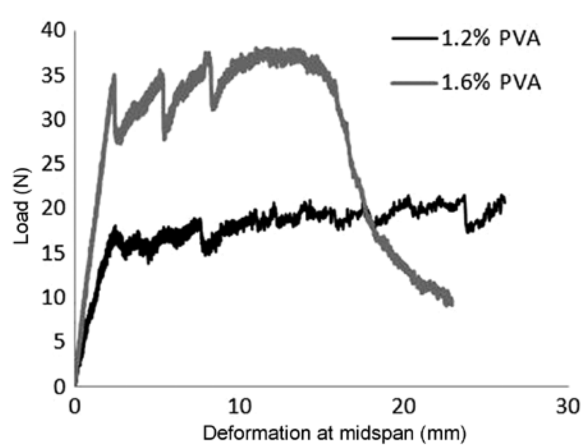


Figure 5 Longitudinal flexural behavior.

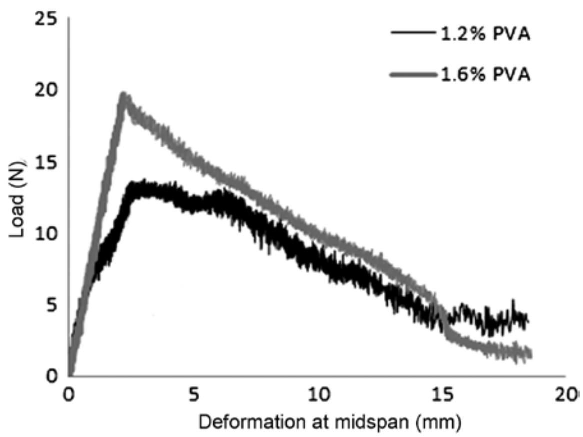


Figure 6 Transverse flexural behavior.

different flexural behaviors, especially in terms of toughness and load-displacement relationships. Toughness, which is the area under the load deflection curve, implies the energy absorption capacity. Cement composites exhibit longitudinal strain-hardening behavior, which is not obtained transversely. Multiple fine cracks are also observed on longitudinal samples that exhibit strain-hardening behavior. A picture of this sample is shown in Figure 7. With multiple fine cracks, the crack arresting and bridging mechanism work and mechanical properties, especially energy absorption, are improved. That the fibers pulled out, instead of rupturing during loading, indicates improved toughness of the composite.

Figure 5, meanwhile, shows the effect of PVA fiber amount on the cement composite flexural behavior of longitudinal samples. By increasing PVA fiber volume from 1.2% to 1.6%, both the energy absorption and the load-bearing capacity of the composite almost doubled. For this type of sample taken from the longitudinal direction, the sample continued to carry the load after the first crack point. A single macro crack also formed at approximately half the total deformation, but the sample continues to exhibit strain-hardening behavior after this singular macro crack occurred. This material started to soften following the localized macro crack.

Figure 6 shows typical flexural behavior of the transverse samples. The behavior differs significantly from that of samples taken from the longitudinal direction. After the peak load is reached, no strain hardening is observed thereafter. Instead, the matrix failed and a macro crack formed after the maximum load at the bend-over point. Following crack formation, softening began as a result of the crack-bridging activity of the fibers. The descending part of the load deflection curve is linear and no sharp decrease is observed. The behavior is still ductile and the decrease in load after it peaked is gradual. Moreover, maximum mid-span deformation for the longitudinal samples is approximately double that of the transverse samples. Longitudinal samples exhibit more ductile behavior than transverse samples. This difference can be attributed to the alignment of PVA fibers with the direction of processing.

Average peak loads under the four-point bending test are given in Figure 8. Fiber content is an effective parameter in the flexural strength of longitudinal samples. Flexural strength is doubled when fiber content increases from 1.2% to 1.6%. Significant improvements of flexural strength are not obtained in the transverse samples even with an increase of fiber content from 1.2% to 1.6%. Figure 8 also shows that the influence of processing direction due to fiber alignment on flexural strength is higher for cement composite samples containing 1.6% fiber.

Figure 9 exhibits the stress-strain behavior of longitudinal samples during tensile testing. During tensile loading, the post-peak behavior of the composite is uncontrollable due to the working mechanism of the system. Although the stress-strain relationships of cement composites of different fiber quantities are identical, the

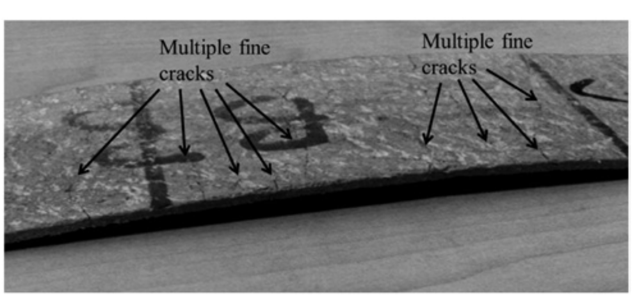


Figure 7 Sample with multiple fine cracks.

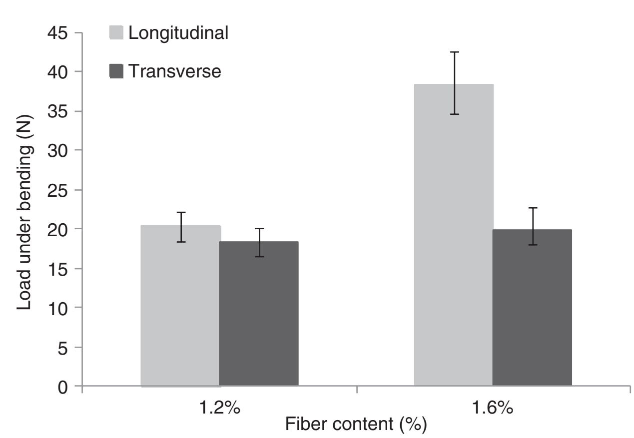


Figure 8 Flexural strength.

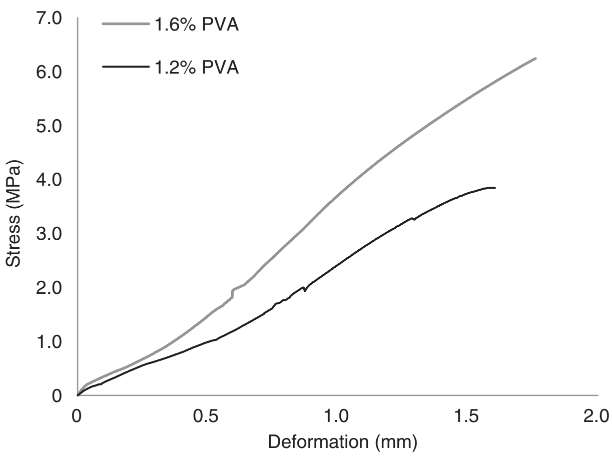


Figure 9 Longitudinal sample tensile behavior.

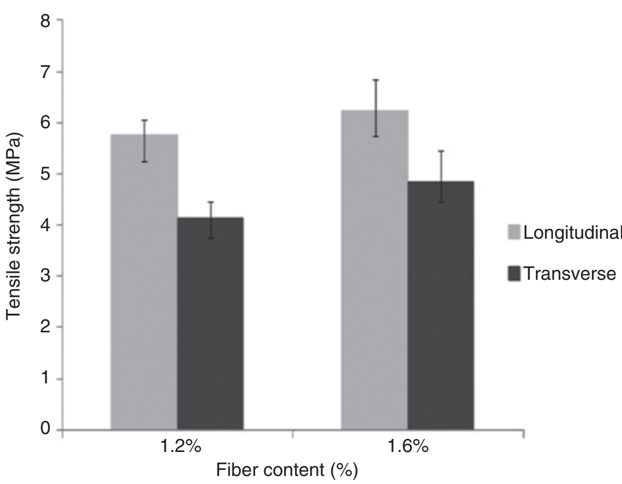
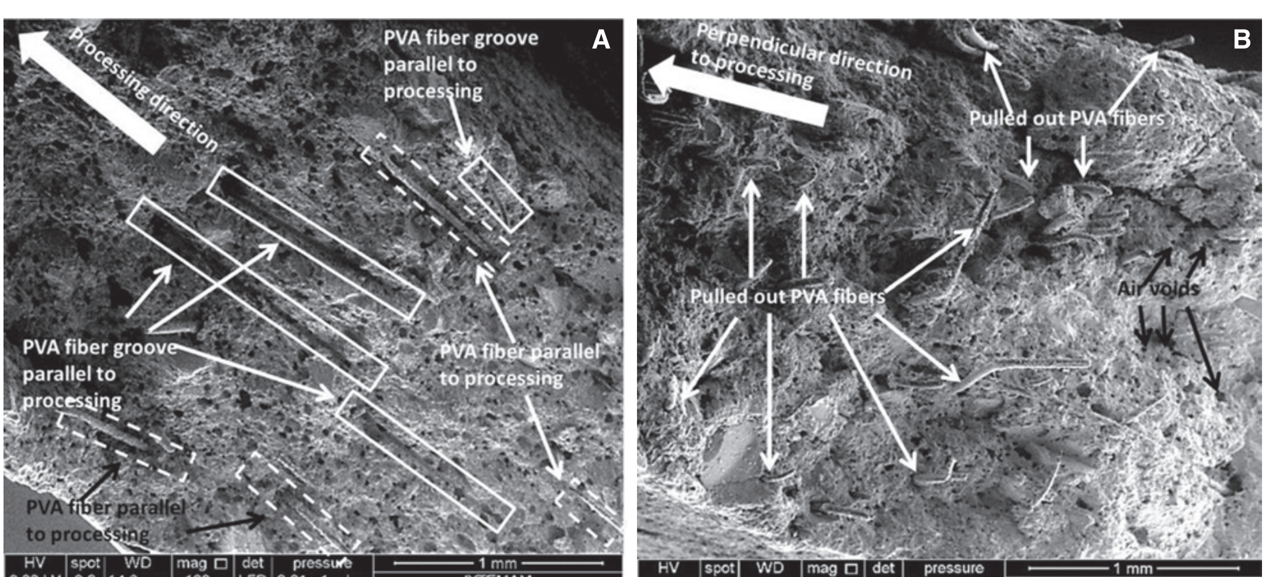


Figure 10 Tensile strength.

tensile strength varies significantly. Tensile strengths of cement composites are given in Figure 10. Processing and sampling direction is a factor that affects the composites' tensile strength. In this study, longitudinal samples have 39% and 29% higher tensile strengths than transverse samples with fiber amounts of 1.2% and 1.6%, respectively.

The microstructure of cement composites may help in understanding the mechanical strength test results. Figures 11A and B show SEM images of fractured surfaces following tensile testing. Figure 11A shows a fractured surface of a transverse sample, while Figure 11B shows a longitudinal sample. As can be seen, the fibers are homogeneously distributed over the fractured surface of the composite. The distances between fibers and fiber grooves also reflect such homogeneity. The low distribution of mechanical strength test results is another indicator of the homogeneous structure. In the results, the alignment of fibers through the processing direction can be easily distinguished. Figure 11A shows PVA fibers parallel to the fractured surface and the grooves of parallel fibers. These grooves and parallel fibers show alignment through the processing direction. A significant amount of fibers perpendicular to the surface is not determined. The same view of fiber grooves and parallel fibers to fracture surface is not observed in Figure 11B. Numbers of pulled-out fibers are obtained on the fractured surfaces of the longitudinal samples. Fiber grooves and amount of pulled-out fibers demonstrate the varying mechanical test results using processing direction. The number of air voids is observed in the cement composite. Lightweight panels, high freeze-thaw resistance due to homogenously



Post tensile test transverse sample Post tensile test longitudinal sample

Figure 11 Post-tensile test SEM images.

distributed tiny air voids, and a lower heat transmission coefficient all indicate the positive effects of air voids on cement composites, while a decrease in material strength demonstrates a negative effect.

The SEM pictures exhibit a fiber matrix interface response. Figures 12A and B show the post-bend fractured surface SEM images of the transverse and longitudinal composite samples, respectively. The morphology of pulled-out fibers on the fracture surface was investigated to determine the bond property. The rough fiber-matrix interface exhibits higher bonding forces generated during loading. The layer of matrix deposited on the pulled-out PVA fibers suggests that good bonding with the fibers is achieved in the cement matrix during mixing, processing, and hardening. In Figure 12A, fibers of the longitudinal samples had more filaments peeled off. The peel-off on the fiber surface shows that the fiber has a strong bond with the matrix. This phenomenon prevents the fiber from being pulled out easily. This strong bond between fiber and matrix corresponds to overall high deformations on the composite during loading. This behavior of the fiber matrix interface is reflected on the specimen in the form of multiple cracks and high deformation rates.

The hydrophilic structure of PVA fibers may be an important factor in bonding performance. The study finds that matrix particles on the PVA fiber are related to chemical bonding between the cement paste and the PVA fibers. Compressive and shear forces during processing can also be important parameters for the desired bonding between cement paste and PVA fiber. The strain hardening of the longitudinal samples is due to the resistance to pulled-out, well-bonded fibers in the matrix, which allows for plastic deformation and high toughness, due brought about by the number of fine cracks that formed.

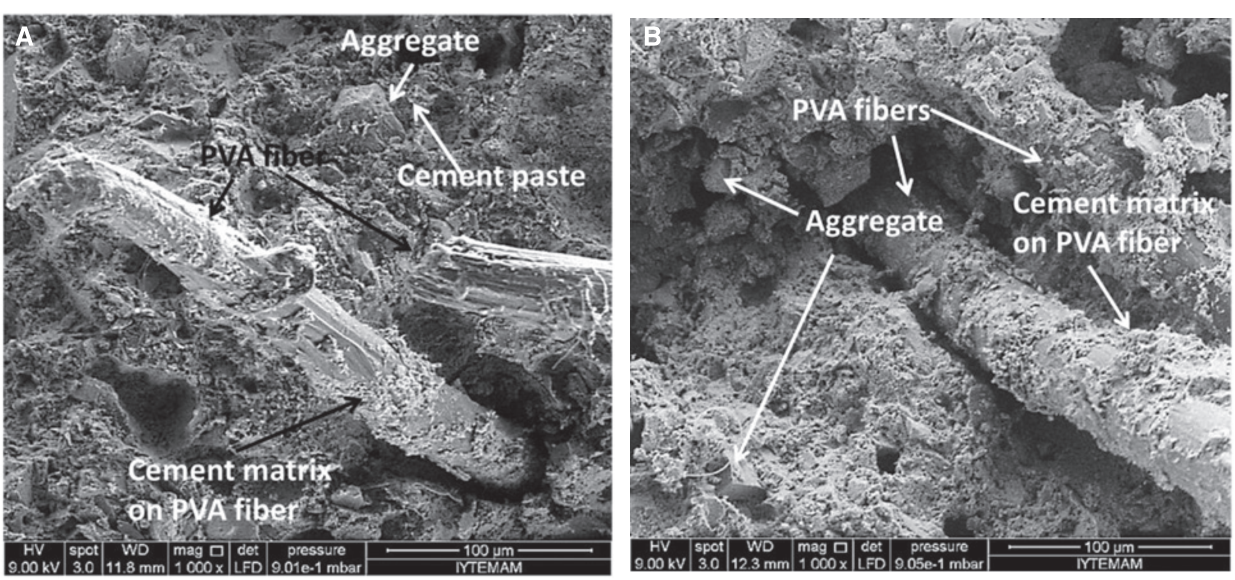
4 Conclusions

According to the results obtained within the scope of this experimental work, several conclusions can be drawn.

Calender extrusion is a promising processing method for thin and versatile cement-bonded fiberboard production. This method aims to produce cement composite panels that have adequate strength and can stand against the external environment. This method also allows rapid mass production of 3D fiber-reinforced concrete elements. Several types of panels with various dimensions have been successfully produced by taking advantage of the dough-like green state sheet material.

Samples showed adequate resistance to freeze-thaw cycles. No noticeable deterioration has been observed after 100 freeze-thaw cycles. The average screw pull through value of 5350 N has been obtained for single screw.

Fibers are aligned due to compression and shear forces between cylinders of the calender extrusion system. This alignment influences mechanical properties. Longitudinal samples have greater flexural strength and toughness, as well as greater tensile strength and deformation capacity than transverse samples. Alignment of the fibers



Post bending longitudinal sample

Post bending transverse sample

Figure 12 Post-bending SEM images.

with processing direction also resulted in strain hardening in the longitudinal samples. Improved toughness has been obtained due to pulled out fibers in longitudinal samples. This behavior has not been observed in transverse samples. The rough fiber matrix interface exhibited higher bonding forces generated during loading, which improved toughness.

Finally, based on the study results, fiber content has been found to be an effective parameter for tensile and flexural properties of processed fiberboards with calender extrusion method. Specifically, higher fiber content prompts higher flexural and tensile strengths and toughness.

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