# Extruded Fiber-Reinforced Composites for Building Enclosures

Katherine G. Kuder[*1], Bin Mu[1], Michele F. Cyr[2], Surendra P. Shah[1]

## Abstract

Extruded fiber-reinforced cementitious composites are excellent candidates to replace conventional building enclosure products. Compared with conventional materials, extruded composites can be stronger, more cost effective, and improve safety in the event of natural hazards. Up to 80% of the cement can be replaced by fly ash, reducing material cost and making the material more environmentally friendly. However, nailing these materials is difficult, usually causing the material to crack. In this work, the ability of extruded materials to be nailed is studied by impact testing and by a newly-developed static nailing test. The results indicate that the type of fiber reinforcement affects impact and static nailing behavior, suggesting that properly fiber-reinforced materials may be nailed. This research also shows that a higher stress rate may be needed to simulate nailing accurately. Consequently, a dynamic test was developed. Once nailing properties are understood, material modifications will be made to produce extruded materials that are nailable.

**Keywords:** fiber-reinforcement, cementitious materials, extrusion process, impact testing, nailing

## Introduction

Cementitious materials can be made to be stronger, more ductile and more durable than conventionally used building materials for building enclosures, such as wall paneling systems, siding and roofing tile. Despite these advantages, however, plain cementitious materials tend to be brittle, with low tensile strength. Special processing techniques, such as extrusion, can be used to overcome these weaknesses by allowing for the addition of a significant amount of fiber reinforcement, up to 8%, by volume. These high-performance fiber-reinforced composites (HPFRC) are ductile, have a high tensile strength and exhibit a strain-hardening response under loading.

Extruded materials offer a number of benefits over the materials currently used for building enclosures. The material shape is not limited to flat sheets, as it is with many conventional processes. Instead, a variety of cross sections, including open sections, can be produced, depending on the intended use. Open sections could be filled with insulating materials, thereby improving home energy efficiency. Extruded materials are environmentally friendly because extrusion machinery pollution output is small and waste materials such as silica fume, fly ash and slag may be incorporated into the material without compromising strength or ductility. Due to the increased strength and ductility of extruded HPFRC, a higher level of safety is provided in the event of natural hazards, such as hail or wind storms. Finally, extruded materials can be

[*] Corresponding author: k-kuder@northwestern.edu.
[1] Northwestern University; Center for Advanced Cement-Based Materials; 2145 Sherdian Rd., Suite A130; Evanston, IL 60208; 847.491.3658 (phone); 847.467.1078 (fax).
[2] E[x]ponent Failure Analysis Associates; 5401 McConnell Ave.; Los Angeles, CA. 90066; 310.754.2778 (phone); 310.754.2799 (fax).

more cost effective than conventional building materials. Machinery costs are less than many setups, including the Hatschek machine, which is currently used for cement-based siding and roofing. Elements are precast, reducing construction time and can be lightweight, decreasing material and transportation costs. In addition, use of waste products reduces the need for cement, decreasing material cost.

Despite these benefits, the issue of nailability still needs to be addressed before cementitious materials can be used for building enclosures. The extruded materials must be able to be nailed the same as conventional products.

## Current "State of the Art"

### *Background*

In the extrusion process, a stiff, highly viscous, fiber-reinforced cementitious dough is forced through a die of desired cross section by either an auger or a ram. The dough must be soft enough to pass through the die, yet stiff enough to maintain its shape upon leaving the die. Consequently, water/binder ratios (w/b) are low, typically around 0.30. After exiting the die, the material is cut and then cured. Either moist curing or steam curing may be used without compromising flexural performance (Peled et al 2000).

Extruded mixes consist of a matrix and fiber reinforcement. Matrices are often complex, containing many additives and admixtures. A variety of waste materials have been successfully incorporated into the matrix, including fly ash (Peled et al 2000), silica fume (Peled et al 2000, Shao et al 2001) and slag (Mu et al 2000). These waste materials are pozzolanic, so they can be used as cement replacements. Research has shown that fly ash can be used to replace up to 80%, by volume, of the cement in extruded materials without any loss in flexural performance (Peled et al 2000). Fly ash has also been shown to improve the rheology of extruded mixes, due to its spherical particle shape, and to increase the durability of composites reinforced with glass fibers by reducing the alkalinity of the matrix. Silica fume helps to achieve a densely packed material, due to its small particle size. Since w/b are low, high-range water-reducing admixtures are needed to improve rheology. Viscosity modifying agents, such as hydroxypropyl methylcellulose, help to bind the water to the solid phases, preventing the migration of water under the high pressure required for extrusion. Latex polymers are sometimes added to improve fiber dispersion and the compactibility of the matrix.

Many fiber types have been used successfully in extrusion, including acrylic, carbon, cellulose, glass, polyethylene terephthalate, polyolefin, polypropylene (PP), polyvinyl alcohol (PVA) and steel (Moras et al 2000; Mu et al 2000; Peled et al 2000; Shao et al 2001; Shao et al 2000; Shao et al 1995). In addition, hybrid combinations of PP, glass and PVA have been successfully extruded (Mu et al 2000; Peled et al 2000). Depending on the fiber type, the strength, ductility, toughness and durability of the extruded composite improve. In hybrid composites, an additive effect was found when combining fibers types (Peled et al 2000). Consequently, hybridization can be used to tailor performance to the desired application.

Different types of composites have been extruded. Thin sheets, pipes and open cellular sheets have been successfully produced (Aldea at al 1998; Stang at al 1996). Lightweight sections, with up to 80%, by volume, of the composite replaced with expanded polystyrene beads, were extruded, reducing material density by 75% (Moras et al 2000).

Extruded HPFRC have high tensile strength, ductility and exhibit a strain-hardening response due to the high amount of fiber reinforcement used and the high shear and compressive forces used to extrude the material. Figure 2 presents typical flexural responses for plain concrete, conventional fiber-reinforced concrete (FRC) and HPFRC. Plain concrete is brittle. FRC, with low fiber reinforcement, around 1%, by volume, shows an increase in ductility, but similar strength to plain concrete. However, HPFRC, with fiber reinforcements from 3-10%, by volume, exhibit a strain-hardening response, with a significant increase in both strength and ductility. Improvement in flexural performance depends on fiber volume fraction (Shao et al 1997) and is attributed to fiber bridging of cracks, multiple and sequential matrix cracking and fiber debonding (Shah et al 1999).

The high shear and compressive forces used in extrusion densify the matrix, improve the fiber-matrix bond and cause fibers to align in the direction of extrusion (Peled et al 2000; Shah et al 1999; Shao et al 2001). When comparing two identical thin sheets, one that was extruded and one that was cast, the improvement in performance due to the extrusion process was seen (Peled et al 2000). The flexural performance of the extruded material was superior to the cast element, with increased ductility, toughness and strength. The extruded matrix was denser than the cast, suggesting an improvement in durability, since the ingress of water and other deleterious agents is more limited.

***Current Work***

The aim of the current research is to produce nailable extruded materials by first gaining an understanding of the fundamental material properties governing nailing and then using this knowledge to develop materials that can be successfully nailed. To accomplish this, the impact and static nailing performance of extruded composites was studied. Next, a dynamic nailing test was developed to simulate nailing more accurately.

For this work, a ram extruder was used. Figure 2 shows the mix design employed. Four fiber types, given in Table 1, were extruded as single reinforcements, or in hybrid combinations. In addition, a plain unreinforced matrix was extruded. When single fiber reinforcement was used, 5%, by volume, of the reinforcement was used, except for the PVA in which only 2% was used, due to rheology limitations. The materials were first mixed by hand and then mixed further in a Hobart mixer, for 10-15 minutes, until a homogeneous material was obtained. The dough was then placed in the extruder chamber, which was mounted onto a 73 kN MTS servo-hydraulic, closed-loop testing machine. The piston, or ram, was lowered at a constant deflection rate of 1.2 mm/sec. The material was cut to the desired length and then steam cured at 90? C for 48 hours.

The impact resistance of extruded thin sheets that were unreinforced, as well as reinforced with PP, glass and PVA fibers, both individually and in hybrid combinations, was tested (Cyr 2003). An instrumented Charpy impact testing machine was used. The specimens were tested in a three-point bend configuration with load cells at the supports and at the striker, or tup. Rubber pads were attached to the specimen at the two supports and at the striker to minimize the parasitic effects of inertial loading (Suaris et al 1981). The impact velocity used was 0.7 m/s. For each test, load and time signals were recorded to determine impact strength, fracture energy and to evaluate whether or not inertial loading was minimized (if it is eliminated, the sum of the two support loads should be equal to the tup load). The flexural performance of the composites was also determined using a static three-point test.

Figure 3 shows the impact strength and fracture energy recorded for the specimens, and Table 2 compares the static and dynamic performance of each. Large scatter can be seen in the data, indicating the sensitivity of specimens to impact loading and the complexities of impact testing. Despite this variability, a few conclusions can be drawn. PP composites exhibit the best impact performance (when comparing impact/static performance) for both impact strength and energy. The PVA composite has a much more brittle response in impact than in static loading, suggesting that it may not be a good candidate for situations in which the loading rate is high. Finally, as was observed in previous research, the effect of hybridization is additive, not synergistic.

With a better understanding of the basic impact performance, two tests were developed to study the nailing properties of extruded materials: a static test and a dynamic test. Unlike the impact test, these tests actually drive a small "nail" through the specimen and evaluate its response to this loading. Two basic parameters were defined to determine nailing properties – nailing load and resistance to cracking. The nailing load is the load required to drive the "nail" through the specimen. This value should be neither too high nor too low. Instead, some optimal range of nailing loads should exist. Resistance to cracking is evaluated by computing the residual flexural strength of the material after a nail has been driven through it (the ratio of the flexural strength after loading to the flexural strength before loading). The higher the residual strength, the less damage sustained due to the nailing load.

To examine the effects of varying fiber types on nailing performance, extruded specimens singly reinforced with PVA, PP, cellulose and glass fibers were tested, as well as a control matrix without fibers. In addition, commercially available materials that are already known to be nailable were tested, to provide insight into the material properties affecting nailability. These materials were Hardie siding, which is a Hatschek-produced, fiber-reinforced cement board, Durock©, a fiber cement board manufactured by USG and common plywood.

The static nailing test used is shown in Figure 4. The initial setup was based on ASTM standard D 1037-99, "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials (ASTM 1999)," the only nailing test arrangement that could be found in the literature. Subsequent testing was undertaken to find the optimal configuration, but is not presented here due to space limitations. For the test, a 177.8 x 50.8 x 8 mm specimen was placed on a nailing plate with a 25.4 mm hole. Tests were conducted on a 73 kN MTS servo-hydraulic, closed-loop testing machine. A cylindrical, flat-tipped "nail," with a diameter of 3 mm, was lowered in deflection control and the maximum nailing load was recorded. Two deflection rates, 45 and 304.8 mm/min, were used to see the effects of stress rates.

Figure 5 presents the nailing load required for each of the extruded specimens at the two nailing rates. Except for the plain material, the extruded materials remained intact during the nailing test, suggesting that at these slow loading rates the materials can be nailed. The results show that nailing rate has little influence on the nailing load. The nailing load, determined for a deflection rate of 304.8 mm/min, for both the extruded and the commercially available materials is shown in Figure 6. The nailing load required for the commercially available materials is less than that for the extruded materials, even the plain, unreinforced matrix, indicating that the extruded matrix alone is stronger in nailing than the commercially available products. In addition, the effect of fibers can be seen. The glass and PVA reinforced composites require the highest nailing load, followed by the cellulose and then the PP.

The residual strength of the materials tested is shown in Figure 7. Except for the plain composite, which had no residual strength since it failed during testing, the residual strengths of the extruded and commercially available materials seem comparable, ranging from 50-98%. This range may seem large; however, it is important to note the Hardie residual strength is only 65%, reasonably close to the fiber-reinforced extruded materials.

Results from the static test seem to indicate that the extruded materials are nailable. However, when these materials are nailed by hand, they split in the direction of extrusion, which is also the direction of fiber alignment, indicating that they cannot be nailed. The reason for this discrepancy is attributed to the slower, constant loading rate used in the static test. Consequently, a dynamic test was developed to test the materials at much higher stress rates, with initial velocities of 0.7 – 3 m/s.

Figure 8 shows the dynamic nailing test developed. Using the same geometry as in the static test, a 177.8 x 50.8 x 8 mm specimen rests on a support plate with a 25.4 mm hole. A nail holder holds the 3 mm “nail” perpendicular to the specimen surface. The striker, or tup, is released and impacts the nail, driving it through the specimen. Similar to the previous impact setup, a rubber pad is placed underneath the specimen to minimize inertial effects, and load cells are located at the two supports and the tup. Nailing load, fracture energy and stress rate will be measured for each initial velocity used. Residual strength will be determined as before, by measuring flexural strength after nailing and dividing it by its initial flexural strength.

**Future Research Directions**

Future work for this project includes the dynamic nailing testing described above as well as a correlation between impact testing and the static and dynamic nail tests. Once a good method to test nailing properties has been developed, the effects of fiber types, hybrid combinations and lightweight compositions will be evaluated. Lightweight composites will include expanded polystyrene beads, perlite and glass beads. Aside from possibly improving nailing properties, these composites will reduce transportation costs and improve the insulating properties of the extruded materials.

**Conclusion**

Fiber-reinforced extruded composites are excellent candidates to replace conventional materials, meeting the PATH goals of improved durability, reduced maintenance costs and reduced damage from natural hazards. To be successfully implemented into the building market, the nailing performance of the extruded material must be improved. Current work has focused on developing testing methods to understand the nailing property of the material. The results show that fiber type influences the material response to impact testing and static nailing, suggesting that the type of fiber reinforcement used may be modified to make is possible to nail the material. Future work includes the dynamic nailing test. Once a good understanding of the fundamental properties governing nailing is obtained, modifications will be made to produce nailable materials.

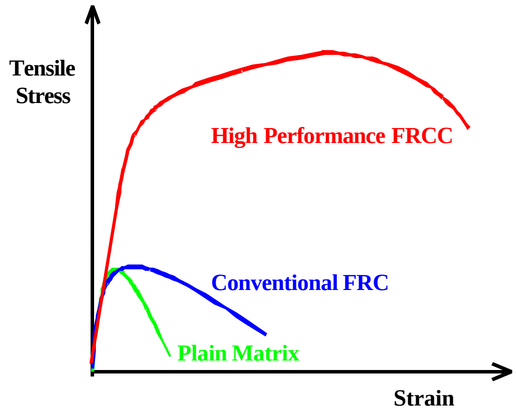


Figure 1: Typical Stress vs. Strain responses for plain concrete, FRC, and HPFRC

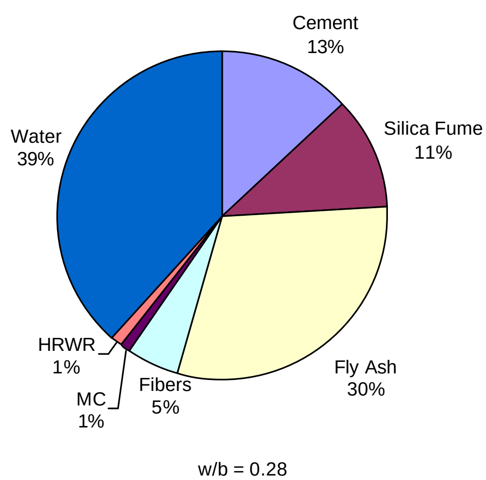


Figure 2: Extruded mix design, by volume

Table 1: Fiber Properties

| Fiber | Tensile Strength (Mpa) | Elastic Modulus (Gpa) | Fiber Diameter (? m) | Fiber Length (mm) | Density ($kg/m^3$) |
|---|---|---|---|---|---|
| **Cellulose Weyerhaeuser Kraft processed** | unknown | unknown | 10 - 15 | ? 2.5 | 1500 |
| **Bundled Glass Cem-FIL 62/2** | 3500 | 71 | 14 | 6 | 2680 |
| **Polypropylene Forta Mighty-Mono** | 700 | 5 | 50 | 13 | 910 |
| **Polyvinyl Alcohol Kuraray RM 182** | 1900 | 41 | 14 | 2 | 1300 |

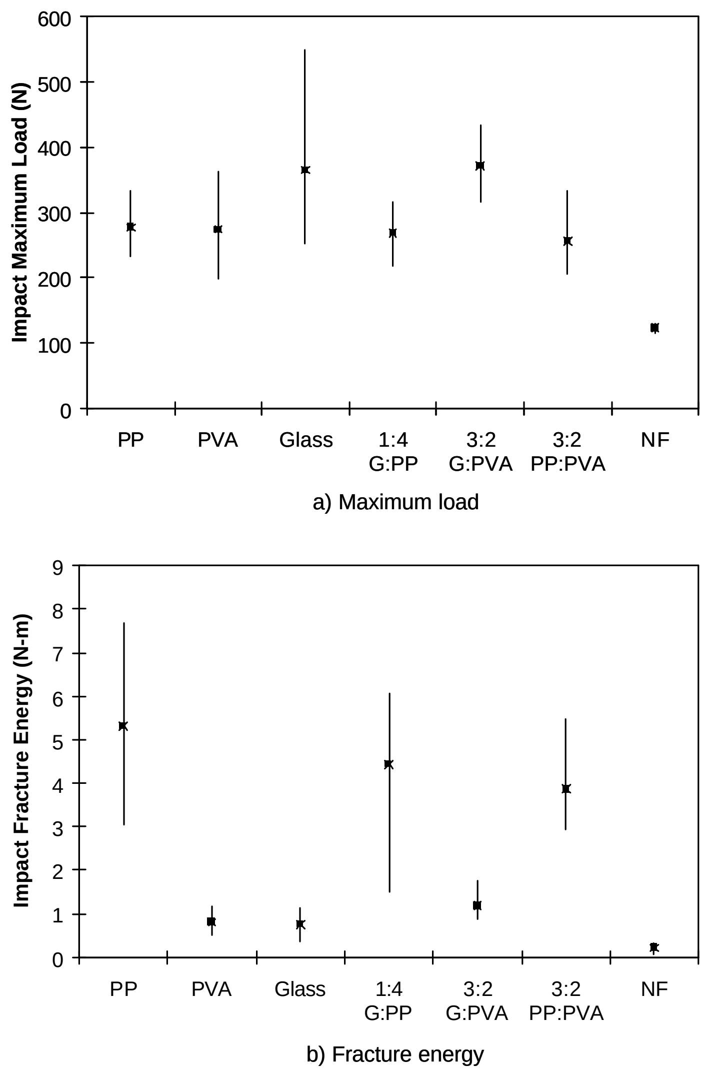


Figure 3: High, low and average values of the impact data: a) maximum load; b) fracture energy

Table 2: Impact/static for maximum load and fracture energy.

| Mix | Impact/Static | |
|---|---|---|
| | **Maximum Load** | **Fracture Energy** |
| **PP** | 4.25 | 4.54 |
| **PVA** | 2.85 | 2.06 |
| **Glass** | 2.15 | 2.94 |
| **1:4 G:PP** | 4.24 | 5.16 |
| **3:2 G:PVA** | 2.81 | 2.75 |
| **3:2 PP:PVA** | 2.69 | 3.97 |
| **No Fibers** | 2.36 | 14.55 |

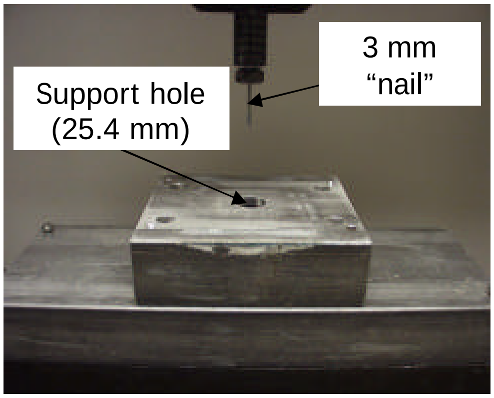


Figure 4: Static impact test

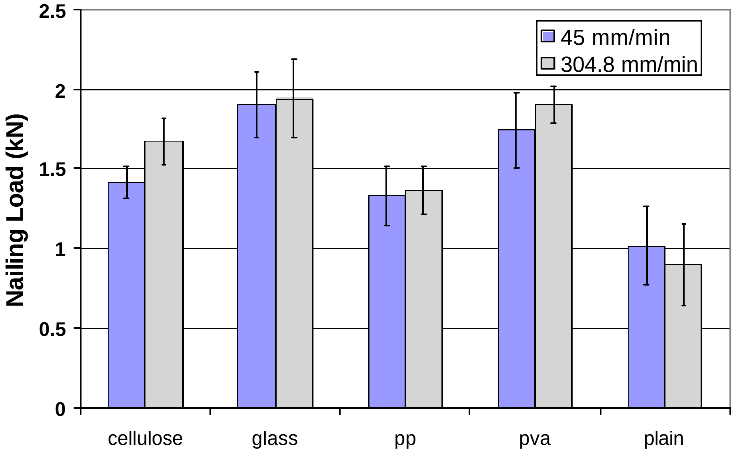


Figure 5: Static nailing load with standard deviations for extruded materials

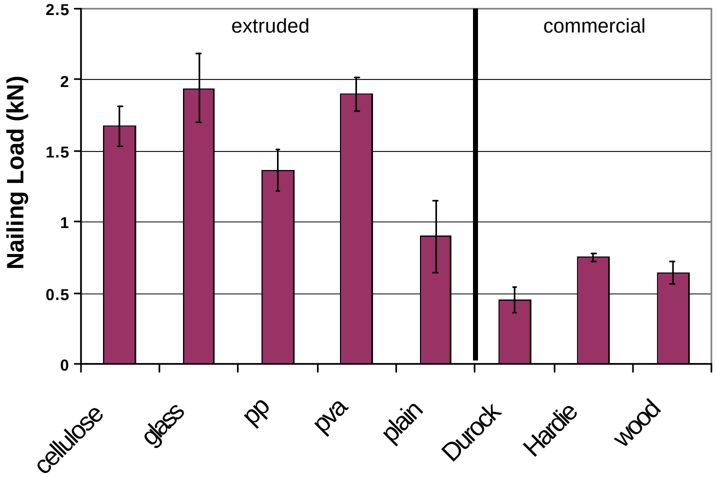


Figure 6: Comparison of static nailing load with standard deviations

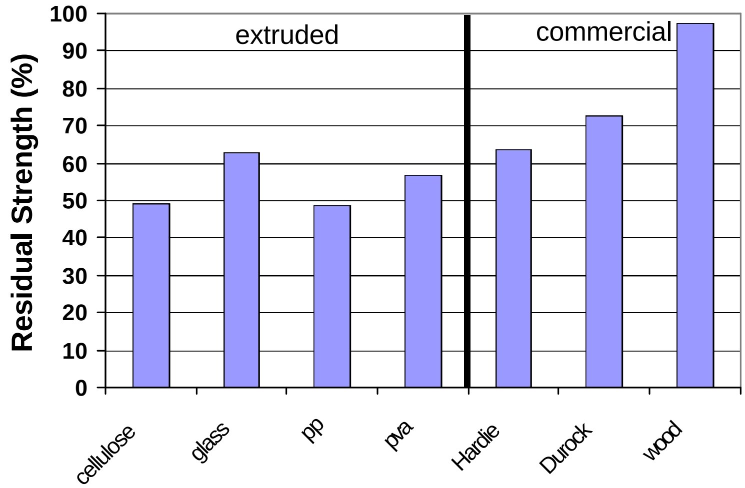


Figure 7: Comparison of residual strength

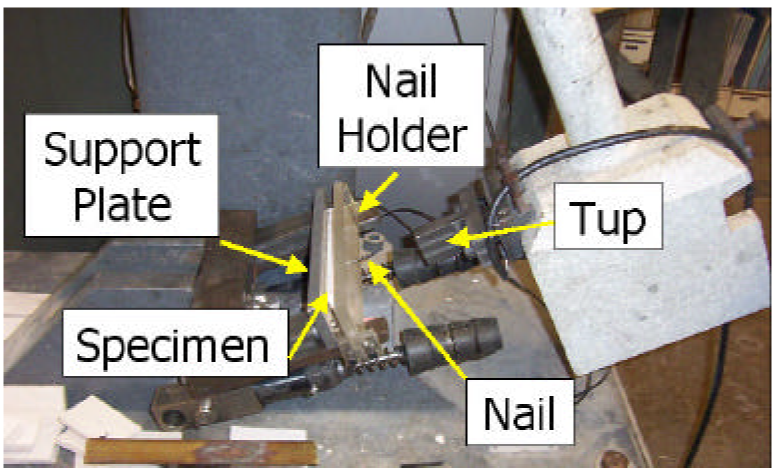


Figure 8: Dynamic nail test

**References**


Aldea, C., Marikunte, S., and Shah, S.P. (1998). "Extruded Fiber Reinforced Cement Pressure Pipe." Advanced Cement-Based Materials Journal. 5(8), 47-55.

ASTM. (1999). "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials." D 1037-99, Philadelphia, PA, 143-172.

Cyr, M.F. (2003). "Hybrid-Fiber Reinforcement in Extruded Cementitious Composites and Cast Concrete." Ph.D. Dissertation, Northwestern University, Evanston, IL, 65-83.

Moras, S., and Shao, Y. (2000)."Extruded Cement-Wood Fiberboard with Expanded Polystyrene Beads." Proc., 7$^{th}$ International Inorganic-Bonded Wood and Fiber Composite Materials Conf., Sun Valley, ID, A.A. Moslemi, ed., 89-103.

Mu, B., Li, Z., and Peng, J. (2000). "Short Fiber-Reinforced Cementitious Extruded Plates with High Percentage of Slag and Different Fibers." Cement and Concrete Research. 30(8), 1277-1282.

Peled, A., Cyr, M.F., and Shah, S.P. (2000). "High Content of Fly Ash (Class F) in Extruded Cementitious Composites." ACI Materials Journal. 97(5), 509-517.

Peled, A., Cyr, M., and Shah, S.P. (2000). "Hybrid Fibers in High Performance Extruded Cement Composites." Proc., International RILEM Symposium BEFIB, Lyon, France.

Shah, S.P., Peled, A., Aldea, C.M., and Akkaya, Y. (1999). "Scope of High Performance Fiber-Reinforced Cement Composites." Proc., 3rd International Workshop on High Performance Fiber-Reinforced Cement Composites (HPFRCC3)., RILEM, Mainz, Germany., 113-129.

Shao, Y., Marikunte, S., and Shah, S.P. (1995). "Extruded fiber-Reinforced Composites." Concrete International. 17(4), 48-52.

Shao, Y., Moras, S., Ulkem, N., and Kubes, G. (2000). "Wood Fibre – Cement Composites by Extrusion." Canadian Journal of Civil Engineering. 27(3), 543-552.

Shao, Y., Qiu. J., and Shah, S.P. (2001). "Microstructure of Extruded Cement-Bonded Fiberboard." Cement and Concrete Research. 31(8), 1153-1161.

Shao, Y., and Shah, S.P. (1997). "Mechanical Properties of PVA Fiber Reinforced Cement Composites Fabricated by Extrusion Processing." ACI Materials Journal. 94(6), 555-564.

Stang, H., and Pedersen, C. "HPFRC-Extruded Pipes." Proc., 4th Materials Engineering Conference, Materials for the New Millenium., Materials Division of ASCE, K.P.Chong, ed., 261-271.

Suaris, W., and Shah, S.P. (1981). "Inertial Effects in the Instrumented Impact Testing of Cementitious Composites." Cement, Concrete and Aggregates. 3(2), 77-83.