

Importance of Processing in Advanced Cement-Based Products

by K.G. Kuder and S.P. Shah

Synopsis: The design versatility of cement-based composites continues to make them attractive for a variety of specialized applications. Advanced processing techniques, including the Hatschek process, extrusion, self-consolidating concrete and slipform-cast concrete paving, offer great promise for improving innovation in the modern construction world. However, to advance the state-of-the-art of cement-based products, the fresh state characteristics of these materials need to be well understood. Processing has a significant impact on composite performance, affecting fresh and hardened state properties as well as overall cost. In spite of its importance, relatively little is known about the relationship between processing and composite performance. Recent work at the Center for Advanced Cement-Based Materials (ACBM), headquartered at Northwestern University, has focused on developing a better understanding of this critical relationship. The role of processing on composite performance has been examined for a variety of advanced processing techniques, including the Hatschek process, extrusion, self-consolidating concrete and slipform-cast concrete paving. The results indicate that overall composite performance can be enhanced by controlling fresh state properties. This paper presents a review of these studies and discusses ongoing research to link composite performance to microstructural changes.

Keywords: extrusion; flocculation; fresh state properties; Hatschek process; processing; self-consolidating concrete; slipform casting

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INTRODUCTION

Cement-based composites offer great design versatility due to their formable nature in the fresh state. As a result, a variety of different processing techniques can be used depending on the intended application. Processing can substantially influence the fresh and hardened state properties of cement-based composites, as well as overall cost. In spite of its importance, relatively little is known about the relationship between processing and composite performance.

Recent work at the Center for Advanced Cement-Based Materials (ACBM), headquartered at Northwestern University, has focused on the effects of processing on composite performance. A number of different processing methods have been studied, including the Hatschek process, extrusion, self-consolidating concrete and slipform paving. The influence of these techniques on composite performance has been systematically investigated. This paper presents a review of the results from these studies as well as discusses ongoing work to link composite performance to microstructural changes.

PROCESSING OF HATSCHEK-PRODUCED COMPOSITES

Introduction

The Hatschek-process is currently used to manufacture fiber-reinforced cement board (FRCB) for non-structural elements in residential construction. The composites are an attractive alternative to wood because they are more fire resistant, can better withstand fading, are not susceptible to insect attack and are more durable. Despite these advantages, use of Hatschek-produced FRCB in colder climates has been limited due to its vulnerability to freeze-thaw attack.

Hatschek process

Figure 1 presents a schematic of the Hatschek formation process. A dilute slurry of cement, silica, water and cellulose fibers is contained in a series of bins. Screens pass through these bins, collecting a monolayer of the material, which is then vacuumed to remove excess water. The monolayers are added to each other as the conveyor belt continues on to subsequent bins. This series of monolayers comes together to form a single layer of the FRCB. Multiple layers are gathered on the accumulator role until the desired thickness is attained. At this point, the composite is then autoclave cured. The resulting FRCB is a laminated composite that is composed of a large volume of cellulose fibers, approximately 30%.

The freeze thaw-durability of FRCB produced by the Hatschek process is poor due to its high porosity, the organic cellulose fibers that reinforce it and its laminated structure. To overcome these weaknesses, some manufacturers have started pressing the FRCB after it is formed, expelling excess water and possibly improving the interlaminar bond (ILB). Research has shown that applying pressure to FRCB improves its mechanical performance^{1,2,3}. The effect of pressure on the freeze-thaw durability of FRCB was investigated, with particular attention to the role of the ILB⁴.

Experimental program and results

Commercial Hatschek-produced FRCB that were 8 mm (5/16 inch) thick, reinforced with cellulose fibers and autoclave-cured were investigated. Immediately after the boards were formed, external pressure was applied at varying levels: 0, 10, 20 and 30 bars. Mechanical testing indicated that pressure increases the flexural strength, decreases flexural toughness (quantified as area under flexural stress – displacement curve) and increases interlaminar tensile strength.

Figure 2 presents the ILB as a function of pressure. ILB increases by 200% from 0 to 30 bars of pressure. Microstructural analyses were conducted using scanning electron microscopy and mercury intrusion porosimetry. These results suggest that the application of pressure improves the fiber-matrix bond and the interlaminar tensile strength by reducing the interlaminar space and the area between the fibers and the matrix^{4,5}.

To assess the freeze-thaw durability of the FRCB, specimens were subjected to as many as 300 accelerated freeze-thaw cycles according to a modified version of ASTM Standard C1185 “Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding Shingles, and Clapboards⁶.” Flexural performance and the interlaminar properties of the FRCB were evaluated after 50, 100, 150, 200 and 300 cycles. The results show that flexural strength decreases after freeze-thaw conditioning. After 50 cycles, flexural strength improves with increasing pressure treatments. However, after more than 50 cycles, pressure treatments do not affect the flexural performance. **Figure 3** presents the ILB strength as a function of freeze thaw cycles and indicates that there is a significant decrease in strength (at least 80% for all materials) after only 50 cycles. However, despite this breakdown of the material structure, there is still a difference in the ILB strength for the different pressures. Even after 200 cycles, the ILB strength of the 30 bar material is twice that of the 0 bar, indicating that pressure may improve the ILB strength.

Visual observations also suggest that pressure treatments do improve the ILB and, consequently, the freeze-thaw durability of the FRCB. **Figure 4** shows 20 and 30 bar materials that have been subjected to 200 freeze-thaw cycles during the three-point bend test. A delamination failure is seen with the 20 bar material, whereas the layers remain in tact for the 30 bar material.

Summary

Overall, the results indicate that modifications to the processing of FRCB can improve the performance of FRCB. Pressure can be applied to freshly formed FRCB to increase the density, improve the fiber-matrix bond, reduce porosity and improve interlaminar tensile strength. FRCB undergoes severe degradation due to exposure to freeze-thaw conditioning; however, the research suggests that some improvement in performance is seen with composites that were pressed.

PROCESSING OF EXTRUDED COMPOSITES

Introduction

Extrusion is an advanced processing technique that is used to produce high-performance, fiber-reinforced cementitious composites (HPFRCC). Extruded HPFRCC are excellent candidates to replace currently-used building enclosure products. Compared with conventional materials, extruded composites can be stronger, more durable, more ductile, more environmentally friendly, more cost effective, offer more design flexibility and improve safety in the event of natural hazards. In addition to enhanced mechanical performance, composites demonstrate a significant improvement in durability due to the high density that results from the extrusion technique^{7,8}. Despite the great potential of extrusion technology, it has not been widely adopted by the North America concrete products industry. One reason for this limited use is that expensive cellulose ether processing aids are needed to control the fresh state properties of extruded materials.

Extrusion technique

In the extrusion process, composites are formed by taking a stiff cementitious dough and forcing it through a die of desired cross section with either an auger or a ram. Mix formulations and processing parameters (extruder barrel and die size, extrusion velocity, etc.) must be carefully designed to optimize fresh state properties. In the fresh state, extruded composites should be sufficiently soft to flow through the die (minimizing extrusion pressure), yet rigid enough to maintain shape upon exiting the die (shape stable). These fresh state properties will in turn affect hardened state properties, including fiber dispersion, composite density and the fiber-matrix bond. Currently, the fresh state properties of extruded composites are controlled using cellulose ethers. However, these materials are expensive. Research at ACBM investigated the effects of processing aids on the extrusion process using extrusion rheology, with an aim at reducing the overall processing aid cost⁹.

Extrudability

Extrudability was evaluated by extruding open cross-sections, using a cellular die, with two cells, that had a total length of 25.4 mm (1 in), a width of 15 mm (0.59 in) and a wall thickness of 3.25 mm (0.13 in). Specimens were

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extruded by a piston extruder at a rate of 1 mm/s (0.04 in/s). If poor shape stability, phase migration, an excessively high extrusion pressure, or surface defects (usually edge tearing) was observed, the material was considered not extrudable. However, it is important to note that extrudability is related to extrusion velocity as well as to the shape being extruded. The minimum amounts of binders defined here are dependent on the velocity and die used.

The matrix composition used, by volume, consisted of 33% Class F fly ash (produced by Dynegy Midwest Generation, Inc., mean particle size = 10 μm), 12% silica fume (W.R. Grace Force 10,000), 14% cement (Lafarge Type I), 39% water and 1% high-range-water-reducing admixture (Daracem 19). Two different cellulose ethers, Methocel (D) and Walocel (W), and two different clay types, Concesol (C) and Metamax (M), were studied. The properties of the cellulose ethers and clays are given in Table 1 and Table 2, respectively. Mix designs are described with the binders of the mix described by weight percentages. For example, W0.25C0.25, contains 0.25% Walocel and 0.25% Concesol. Mixes were prepared using a planetary (Hobart) mixer. A piston extruder, mounted in a closed-loop, MTS hydraulic testing machine with a 24 kN (5.4 kips) load cell, was used with a barrel diameter of 38.1 mm (1.5 in) and a length of 125 mm (4.92 in).

Table 3 summarizes the extrudable mixes. In the absence of clay binders, half the amount of W was required compared to D. Figure 5 shows the effect of clay on extrudability. Once 0.3% of the clay was added, an extrudable mix was achieved. Similar results were found when either C or M was added. However, if all the cellulose ether was removed, the material was no longer extrudable. These results indicate that it is important to find the most effective type of cellulose ether (here twice as much D is needed, compared to W, while the costs are comparable) and that cellulose ethers can be partially replaced with clay binders.

Capillary rheology

Capillary rheology was used to describe the fundamental flow properties of the extruded mixes. The analysis assumes that flow is laminar (Reynolds number < 2000), is fully developed and that there is no slip at the wall. The apparent shear stress (τ_{app}) and shear rate ($\dot{\gamma}_{app}$) are given in Equation (1) and (2), respectively.

$$\tau_{rx} = \tau_{app} = \frac{PD}{4L} \quad (1)$$

$$\dot{\gamma}_{app} = \frac{8V}{D} \quad (2)$$

Where P is the extrusion pressure (kPa or psi), V is the mean extrudate velocity in the capillary (mm/s or in/s), L is the capillary length (mm or in) and D is the capillary diameter (mm or in). End effects are taken into consideration using Bagley's end correction¹⁰, which determines the true wall shear stress in the capillary, τ_w , by:

$$\tau_w = \frac{PD}{4(L + ND)} \quad (3)$$

Where N is the end correction factor for the imaginary extension of the capillary length.

Capillary analysis was conducted by extruding mixes through three different die lengths at six different velocities. Three die lengths (giving L/D = 1, 2 and 4) and six piston velocities, 0.2, 0.5, 1, 2, 3 and 5 mm/s (0.008, 0.020, 0.040, 0.079 and 0.197 in/s), which correspond to extrudate velocities of 1.8, 4.5, 9, 18, 27 and 45 mm/s (0.071, 0.178, 0.354, 0.709, 1.063 and 1.772 in/s), respectively, were used.

Figure 6 presents an example of a rheometric curve obtained using capillary analysis. Yield stress (τ_0) was approximated using the lowest two data points and extrapolating to the y-axis. Using the differential viscosity versus apparent shear rate curve, an equilibrium viscosity ($\eta_{equilibrium}$) was defined as the differential viscosity at which the system equilibrated.

Figure 7 presents the two parameters plotted together, for both the extrudable and not extrudable mixes, and demonstrates that, when considered together, τ_0 and $\eta_{\text{equilibrium}}$, can be used to evaluate extrudability. **Figure 7** suggests that an extrudable mix is one in which the yield stress is reasonably low (facilitating extrusion) and the equilibrium viscosity (probably related to thixotropy) is high. It is interesting to note that the zone of extrudability, with low yield stress values and high viscosities, is similar to the zone of rheological parameters required for self consolidating concrete¹¹, which requires a low yield stress and a high viscosity. The similarities with these rheological parameters suggest that both the yield stress and viscosity (related to cohesion) are important factors to describe flow behavior.

Summary

Clay binders were found to be suitable partial replacements for cellulose ethers, significantly reducing the cost of the extruded composite. Capillary rheology was used to describe the fresh state properties for extrusion and showed that extruded HPFRCC have high equilibrium viscosities and low yield stresses.

FIBER-REINFORCED SELF CONSOLIDATING CONCRETE

Introduction

Self consolidating concrete (SCC) is concrete that is highly deformable in the fresh state, flowing under its own self weight without segregating. This technology is suitable for applications in which complicated shapes are being formed and in cases where congested reinforcement is used. SCC eliminates the need for external vibration, reducing labor and energy costs. Furthermore, when properly designed, the hardened state properties of SCC can be superior to conventional concrete, with a more homogeneous matrix and better bonding to reinforcement. The extension of this technology to fiber-reinforced self consolidating concrete (FRSCC) offers great promise, likely producing composites that exhibit superior mechanical performance and durability due to the enhanced fiber-matrix bond and greater compactness. Recent research efforts have focused on developing methodology to design fiber reinforced SCC to optimize fresh state properties, which should in turn enhance hardened state properties¹².

Rheological paste model – solid skeleton grading

The “rheology of paste” model developed by Saak and colleagues¹³ has been modified to account for fiber reinforcement. The model determines the minimum volume of cement paste needed to allow for the required deformability and segregation resistance by analyzing the optimum grading for the solid skeleton system. The average aggregate spacing, d_{ss} , which is twice the thickness of the excess paste layer coating the aggregates, is determined according to:

$$d_{ss} = d_{av} \left[\sqrt[3]{1 + \frac{V_{paste} - V_{void}}{V_{concrete} - V_{paste}}} - 1 \right] \quad (4)$$

Where d_{av} is the average diameter of the solid skeleton particles, V_{paste} , V_{void} and $V_{concrete}$ are the volumes of the paste, voids and concrete, respectively. Fibers are treated based on an “equivalent spherical particle” fraction based on the specific surface of the fibers such that an equivalent diameter, $d_{eq-fibers}$, can be calculated by:

$$d_{eq-fibers} = \frac{3L_f}{1 + 2\frac{L_f}{d_f}} \frac{\gamma_{fiber}}{\gamma_{aggregate}} \quad (5)$$

Where d_f and L_f are the diameter and length, respectively, of the fibers, γ_{fiber} is the specific weight of the fibers and $\gamma_{aggregate}$ is the weighted average of the specific weight of all the aggregates. Finally, the average equivalent diameter of the solid particles, d_{av} , is determined:

$$d_{av} = \frac{\sum_i d_i m_i + d_{eq-fibers} m_{fibers}}{\sum_i m_i + m_{fibers}} \quad (6)$$

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Where d_i is the average diameter of the aggregate fraction (defined as the average size opening of two consecutive sieves), m_i is the mass of the aggregate fraction and m_{fibers} is the mass of the fibers.

Rheological characterization

The rheology of the cement paste is characterized using the mini slump-cone test and rheometer tests. Mini slump-cone tests were used to determine flow diameter (related to yield stress) and rheometer tests employing a concentric cylinder geometry, along with equilibrium shearing protocol, indicated the apparent viscosity. These two parameters were considered jointly using the ratio of the flow diameter/apparent viscosity.

Application of model

The optimum flow diameter/viscosity ratios for self compactability were determined as a function of the average aggregate spacing, d_{ss} , as is shown in [Figure 8](#). Three zones are shown: segregation, allowable (self consolidating) and poor deformability. These zones were determined based on experimental data using regression analysis. Fiber dispersion was analyzed by evaluating the amount of fibers in the top, middle and bottom thirds of cylindrical specimens and the effects included in the model based on segregation tendencies. The model lines show that minimum and maximum flow diameter/apparent viscosity of the cement paste are needed to achieve sufficient deformability and prevent segregation, respectively. As the average aggregate spacing decreases, the required flow diameter/viscosity increases, suggesting a greater flow diameter and lower viscosity are needed for self consolidation. Furthermore, a larger range of possible flow diameter/viscosity exists for larger average aggregate spacing, indicating more design flexibility.

The concept of optimum limiting values of flow diameter/viscosity for varying average aggregate spacing can be used to design FRSCC. Rheology tests are used to analyze the cement paste, while the grading of the optimum solid skeleton is determined through the measurement of the average diameter of the particles and the void ratio. The correlation between cement paste rheology and solid skeleton grading is then determined. Based on this relationship, the allowable values for the average spacing of solid particles as well as the cement paste rheology and solid skeleton grading can be determined.

The proposed model was used to design three FRSCC containing the same cement paste and 50 kg/m^3 of steel fibers (Dramix 65/35), but which fell within the different mix design zones – poor deformability, self-compacting and poor segregation resistance for mixes A, B and C, respectively.

[Figure 9](#) presents the results of this analysis. The cement paste had a flow diameter/viscosity of 650, V_p varied from 0.32, 0.36 and 0.40, and d_{ss} ranged from 0.272, 0.360, and 0.460, corresponding to mixes A, B and C, respectively. Slump tests, a visual segregation index and the T_{50} slump flow test (time required to reach 50 mm diameter spread) were used to assess and verify that the intended fresh state properties were achieved. These results indicate that a rational method can be used to design FRSCC.

Summary

A methodology has been developed to design FRSCC that considers the effect of the cement paste rheology and the solid particle skeleton (considering the contribution of the fibers via an equivalent spherical particle fraction) on fresh state properties and fiber dispersion. The results indicate that through the use of optimum limiting values of slump flow diameter/viscosity for varying average aggregate spacing, mixes that exhibit self consolidating behavior can be achieved.

SLIPFORM PAVING

Introduction

Currently, concrete pavement is placed using a slipform paving machine. Slipform paving is a continuous process in which the concrete is poured, consolidated and finished as the paving machine moves at a constant rate over the fresh concrete. The concrete is a low slump concrete (less than 5 cm [2in]) that maintains its shape without edge support once placed. To consolidate the concrete, equally spaced internal vibrators are used. However, if the frequency is not properly selected, or if the paving machine moves too slowly, the concrete can become over-vibrated. The result of this over vibration is aggregate segregation, a reduction in air-entrainment and vibrator trails that are a source of inherent weakness. To resolve this issue, a low compaction energy concrete has been designed that does not require vibration¹⁴. The concrete demonstrates both a high workability and a high shape stability.

Strategy

Figure 10 depicts the strategy adopted to produce low compaction energy concrete. A typical SCC mix design (i.e. one with high workability) was taken and modified using various mineral (fly ash, clays) and chemical (plasticizers, viscosity modifying admixture) admixtures to achieve shape stability. Flowability was evaluated using a flow test and a drop table test. Results from the drop table test were also used to assess shape stability. In addition, compression strength tests were conducted on freshly-mixed concrete samples to determine green strength. Finally, a model paver that was constructed to simulate the slipform paving process in the laboratory was used to evaluate the compaction ability of the concrete.

Experimental results

The effect of plasticizers and fine materials on the flowability and green strength of concrete was determined. The results are presented elsewhere, but summarized here¹⁴. The amount of additive needed to achieve a flow ratio of zero (i.e. shape stability) was obtained by beginning with a typical SCC mix design and then reducing or increasing the amount of plasticizer or fine material, respectively. Flowability and green strength of the shape stable mixes were then evaluated using the drop table tests. These results show that by properly tailoring the type and amount of plasticizer and fine material(s) in a mixture, both shape stability and flowability can be achieved.

The relationship between green strength and the flow ratio after 25 drops is presented in **Figure 11**. As expected, a general trend exists whereby green strength reduces dramatically with the flow ratio. However, it is interesting to note that some mixes do not follow this trend. These mixes contain the naphthalene-based plasticizer, or fine materials (clay or fly ash). Further research is needed to understand this trend.

Figure 12 shows different mixes that were cast using the laboratory-scale slipform paver for four different mixes: typical slipform, modified plasticizer (naphthalene-based), and two with clay additives. The last three of these are mixes that were shown to have desirable flowability and shape stability. These composites demonstrate excellent shape stability, edge stability and flowability when cast without vibration.

Summary

Concrete mixes were successfully designed for slipform paving applications that can be cast without applying vibration. Mixes were developed using the concept of SCC and modified to obtain shape stability. The effect of additives on the flowability and shape stability was evaluated. A good correlation was observed between high flowability, shape stability and the ability to be formed without vibration using a simulated slipform paver.

FUTURE DIRECTIONS: THE STUDY OF FLOCCULATION

Introduction

Advanced processing techniques rely on microstructural changes that occur during the first few hours of the life of concrete. Applications such as extrusion, self consolidating concrete and slipform casting require cementitious systems that are highly flowable yet shape stable. Ongoing work at ACBM is investigating how admixtures, including plasticizers, clays and fly ash, affect the flocculation behavior of cement paste. It is hypothesized that flocculation is related to shape stability (green strength).

Compressive rheology and green strength

The flocculation behavior and green strength of different cement pastes were investigated. Flocculation behavior was examined using the centrifugal approach in which the compressive yield stress is measured as a function of local particle volume fraction. In addition, green strength was measured. Six different mixes were investigated: control (CM), cement and Class C fly ash (FA), cement and naphthalene-based plasticizer (HW), cement and purified magnesium aluminosilicate clay (C1), cement and kaolinite, illite, quartz clay (C2) and cement and kaolinite clay (C3). The water/binder ratio was approximately 0.40.

Figure 13 presents the compressive yield stress of the six different mixes as a function of local volume fraction. These results show that the HW and FA mix are more compressible than the control (CM), whereas C1, C2 and C3 have a higher compressive yield stress. These findings correlate well with green strength testing, which shows that the HW and FA have green strengths that are lower than the CM, while the C1, C2 and C3 have a greater green strength than the CM. Thus, flocculation appears to be related to green strength.

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Summary

Enhanced fresh state properties have been achieved by controlling workability and green strength. The flocculation of particles in the cement paste mixes was studied using compression rheology and shows good agreement with green strength. These results suggest that flocculation is an important mechanism to understand and control for the processing of advanced cement-based composites.

CONCLUSION

Recent work at the Center for Advanced Cement-Based Materials (ACBM), headquartered at Northwestern University, demonstrate the potential of cement-based composites to be used in a variety of specialized applications. The success of these new technologies relies on advanced processing techniques in which the fresh state properties must be controlled and optimized. The role of processing on composite performance has been examined for the Hatschek process, extrusion, self consolidating concrete and slipform-cast concrete paving. The results indicate that overall composite performance can be enhanced by controlling fresh state properties. Furthermore, ongoing research suggest that by studying the behavior of the microstructure at early ages, in particular with respect to flocculation, the mechanisms by which enhanced fresh state properties are achieved can be understood.

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Table 1 – Properties of cellulose ethers

Trade name	Producer	Chemical designation	Specific gravity g/cm ³ (lb/in ³)	Viscosity Pa*s (psf*s)
Methocel 4fm [*]	Dow Chemical Company	Hydroxypropyl methylcellulose	1.3 (0.05)	2.3-3.8 (0.05-0.08)
Walocel M-20678 ^{**}	Wolff Celulosics	Methylhydroxyethyl cellulose	3.2-4.0 (0.12-0.14)	10.4-12.4 (0.22-0.26)

^{*} Viscosity determined for 1% solution, 20° C, Rotovisko rheometer

^{**} Viscosity determined for 1% solution, 20° C, "by rotation"

Table 2 – Properties of clay binders

Trade name	Producer	Mineral Composition	Mean particle size µm (µin)
Concresol	Stephan Schmidt Group	kaolinite (45%), mica (35%) and free silica (20%)	≈ 0.5 (20)
Metamax HRM	Engelhard	calcined kaolinite	1.2 (47.2)

Table 3 – Extrudable mixes

(a) D

Material	Extrudable
D0.5	
D1	x
D2	x
D0.5/C0.15	
D0.5/C0.3	x
D0.5/C3	
D0.5/M0.15	
D0.5/M0.3	x
D0.5/M3	

(b) W

Material	Extrudable
W0.25	
W0.5	x
W1	
W0.25/C0.15	
W0.25/C0.3	x
W0.25/C3	
W0.25/M0.15	
W0.25/M0.3	x
W0.25/M3	

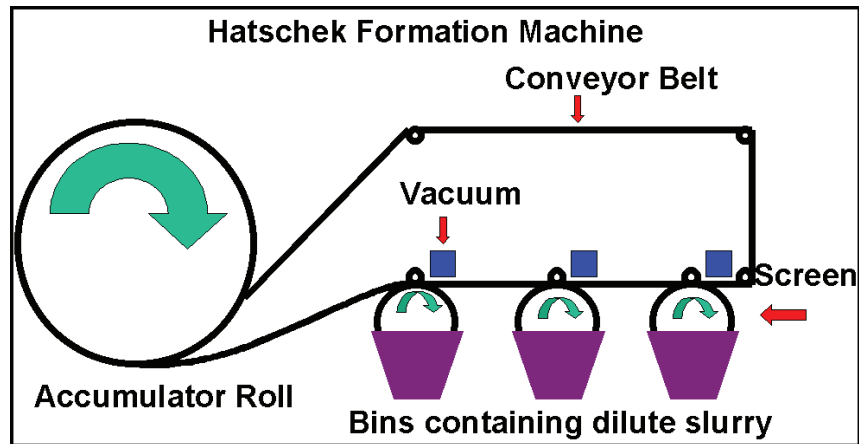


Figure 1 – Schematic of Hatschek slurry-dewatering process.⁴

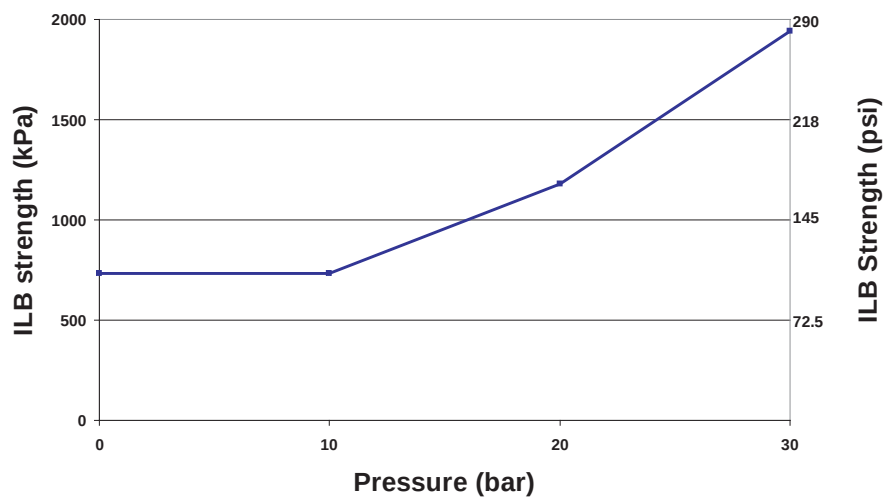


Figure 2 – Interlaminar tensile bond (ILB) strength as a function of pressure.⁴

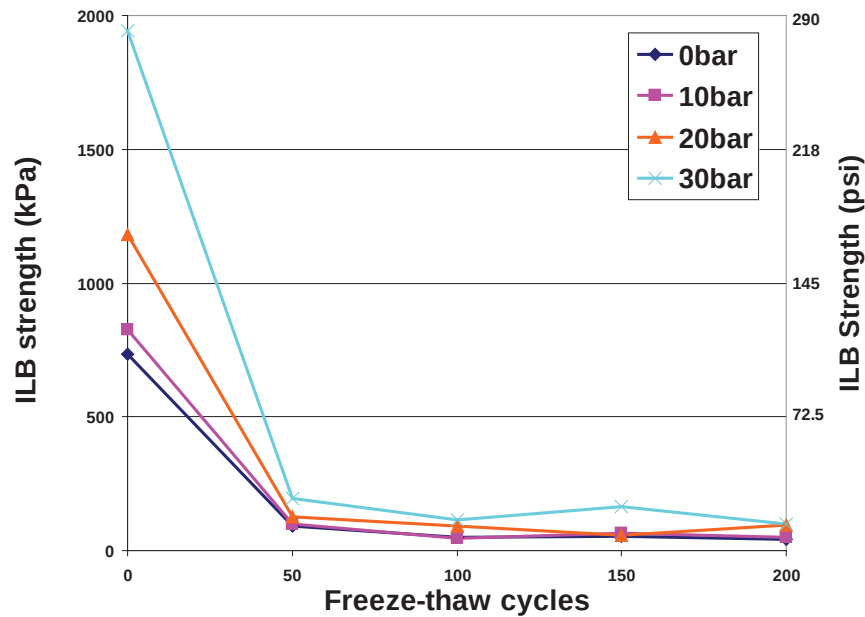


Figure 3 – Interlaminar tensile bond strength (ILB) as a function of freeze-thaw cycles for different pressure treatments.⁴



(a)



(b)

Figure 4 – FRCB specimens during three-point bend test after 200 freeze-thaw cycles for pressure treatments of: (a) 20 bar; and (b) 30 bar.⁴



0.25W



0.25W0.15C



0.25W0.3C



0.25W3C

Figure 5 – Example of effect of clay on extrudability (Walocel and Concretol combinations shown here).⁹

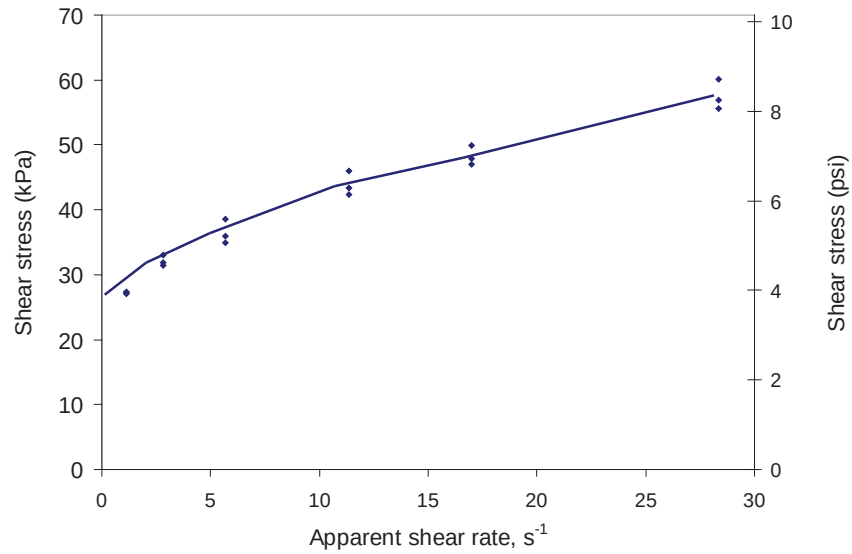


Figure 6 – Example of shear stress versus apparent shear rate (Walocel 0.5 shown here).⁹

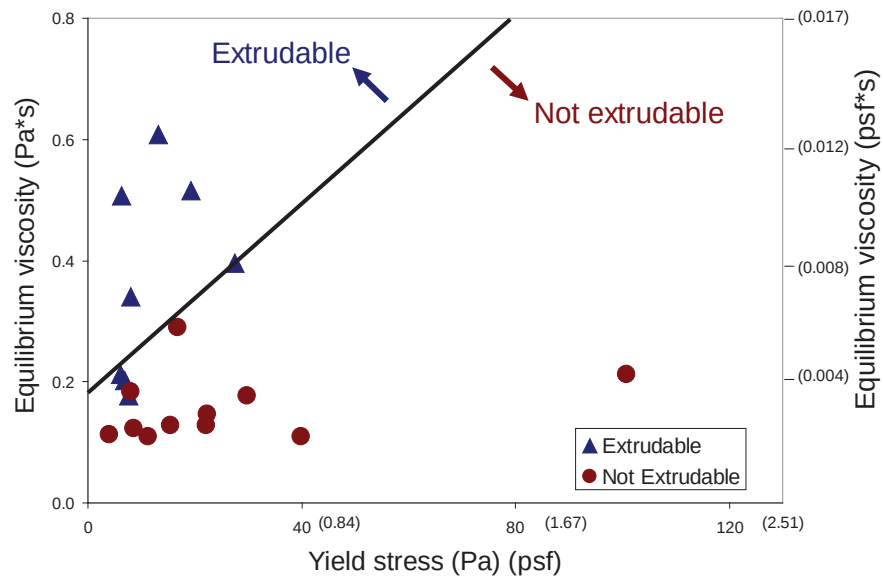


Figure 7 – Equilibrium viscosity versus yield stress for extrudable and nonextrudable mixes.⁹

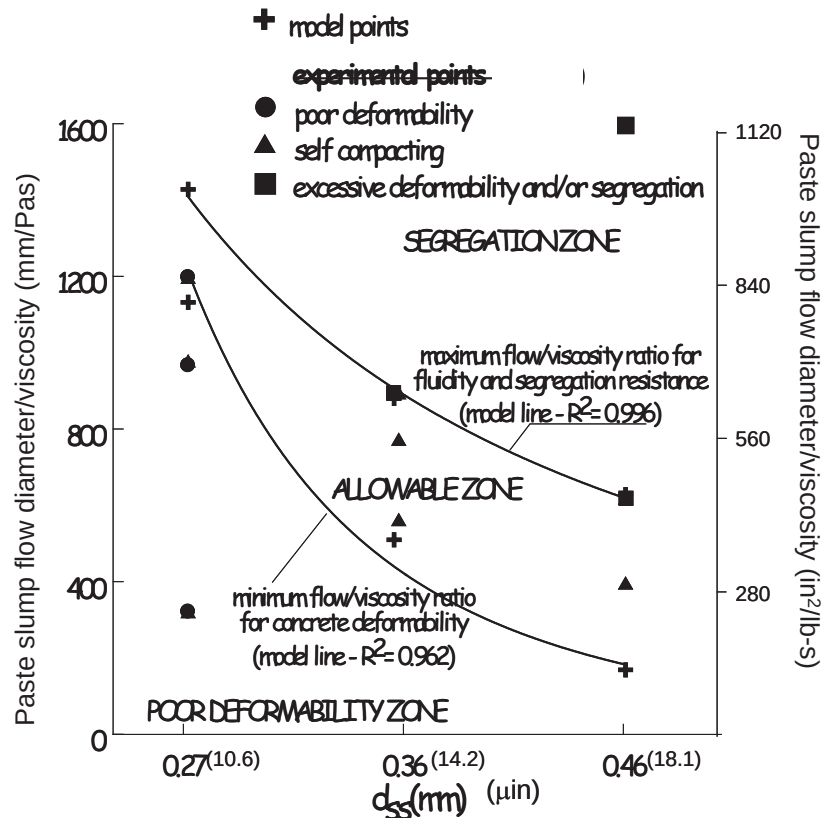


Figure 8 – Paste slump flow diameter/ viscosity ratio as a function of average aggregate spacing, d_{ss} (model lines and experimental data).¹²

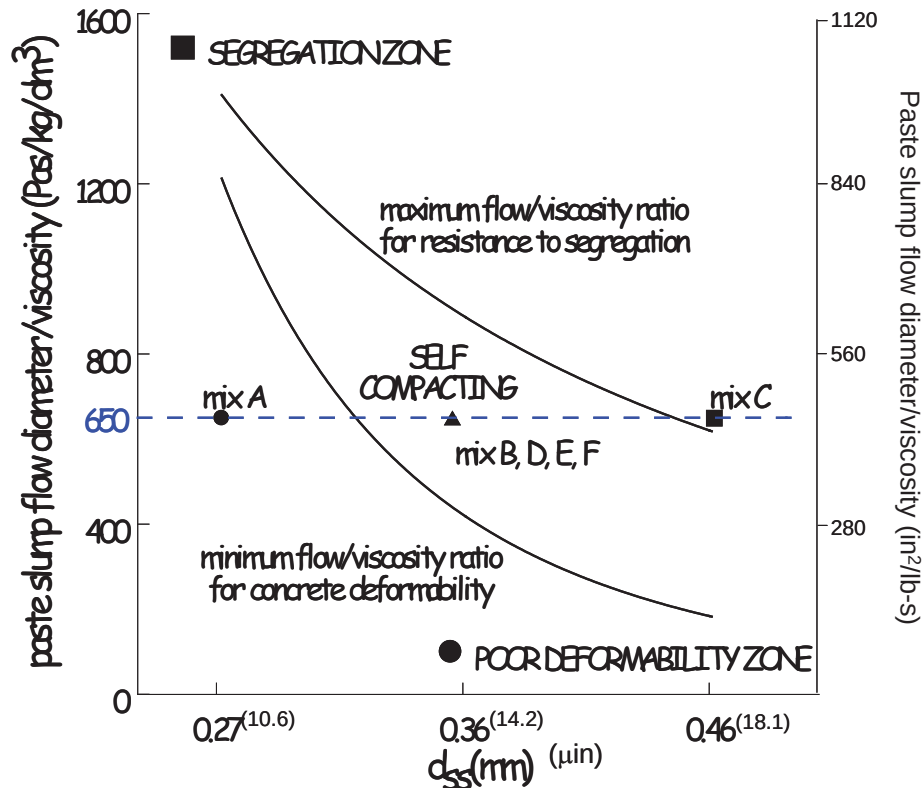


Figure 9 – Paste slump flow diameter/ viscosity ratio as a function of average aggregate spacing, d_{ss} , for three concrete mixes with different deformability to demonstrate model effectiveness.¹²

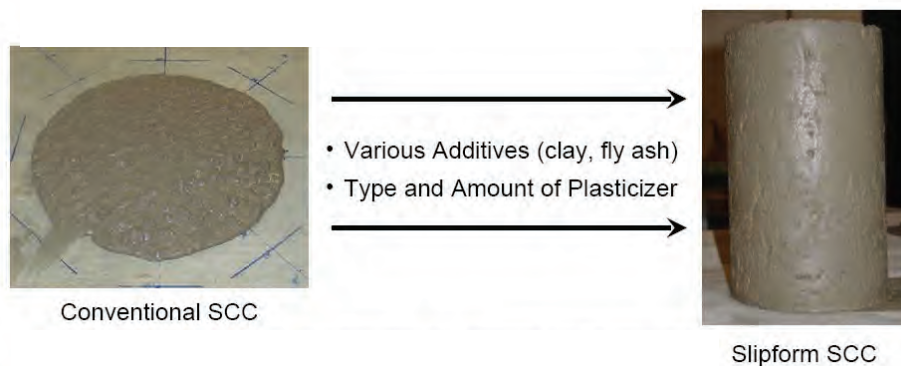


Figure 10 – Concept of producing low compaction energy slipform paving concrete.

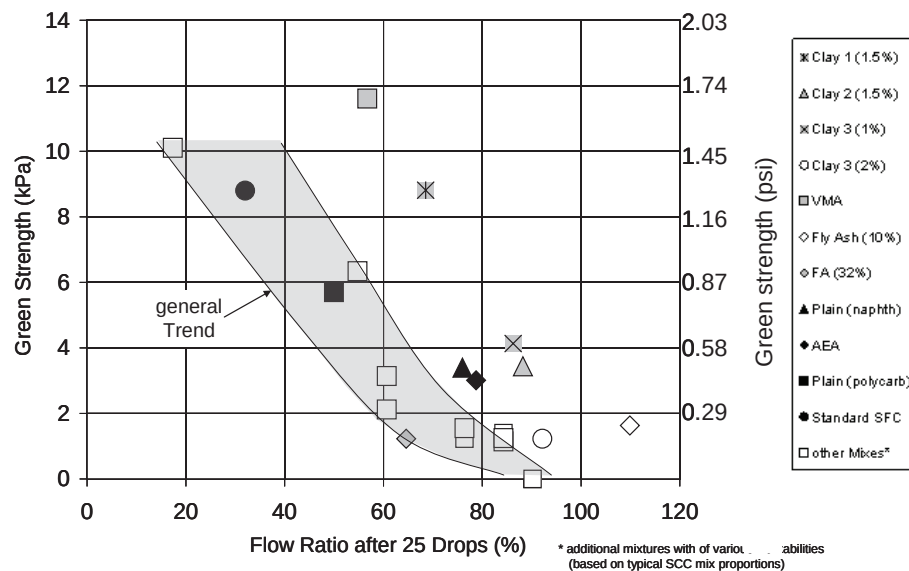


Figure 11 – Green strength as a function of flow ratio for variety of mixes.¹⁴

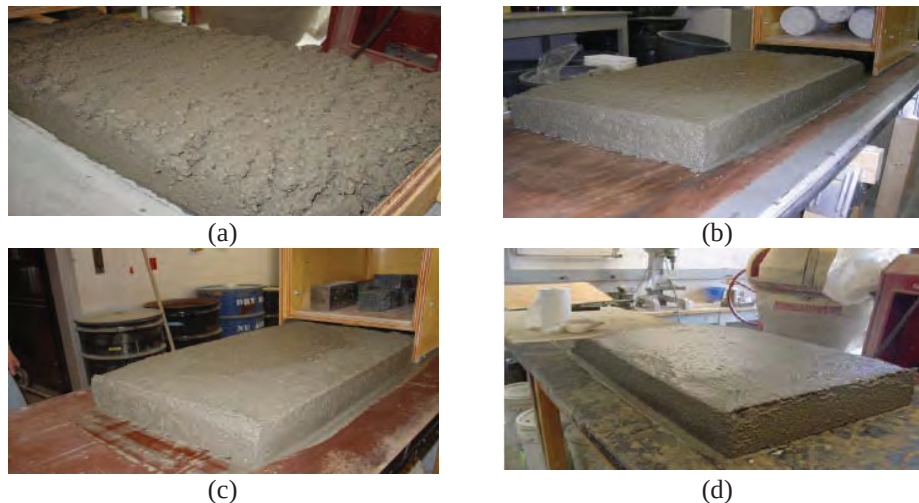


Figure 12 – Concrete slab in fresh state produced with model laboratory paver without internal or external vibration for: (a) typical slipform paving concrete; (b) modified SCC with naphthalene-based plasticizer; (c) SCC with 0.32% volume Metamax; and (d) SCC with 0.32% volume Conoresol.

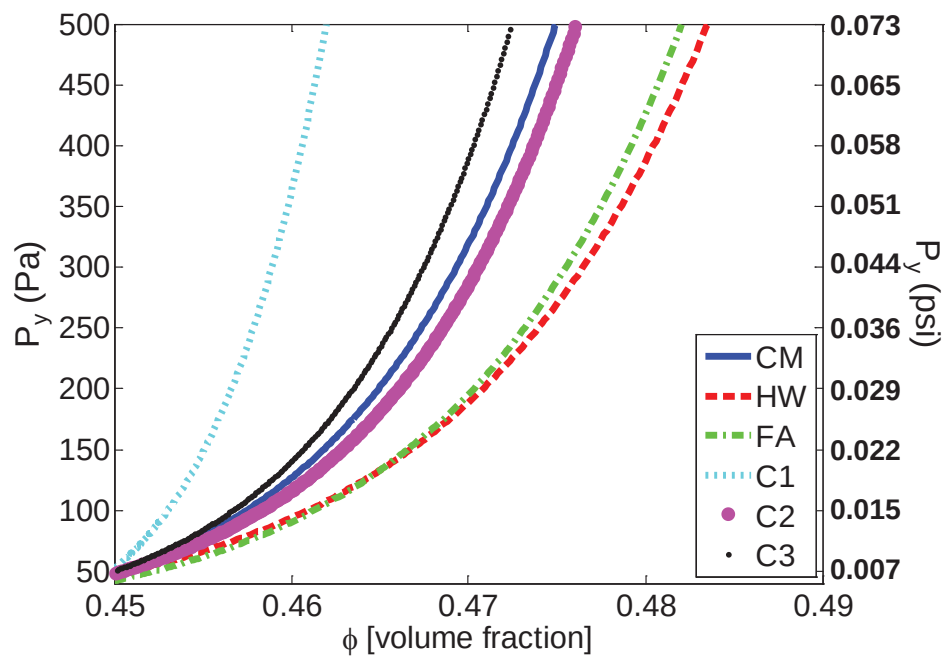


Figure 13 – Compressive yield stress as a function of local volume fraction of cement paste for control (CM), superplasticizer (HW), fly ash (FA), purified magnesium aluminosilicate clay (C1), kaolinite, illite, quartz clay (C2) and kaolinite clay (C3).

Development of Thermal Insulation and Storage Materials Using Extrusion Technique

by X. Li and Z. Li

Synopsis: Thermal insulation and thermal energy storage are becoming more and more attractive for residential and industrial buildings due to the need of sustainable development. The economical and efficient technique that can be used to produce building products for insulation and store energy is also the subject of research for a long time. Cement-based products manufactured by extrusion technique offer advantages in terms of the flexibility of section profiles, material performance enhancement and mass production mode. Different fillers can be used to achieve desired effects on thermal, mechanical and physical characteristics during extrusion process. These fillers include sand and expanded perlite which are good at thermal insulation and phase change composites which can provide high energy storage capacities. It is foreseeable that extruded building products with suitable fillers have potentiality for economical applications for thermal insulation and thermal storage of different kinds of buildings.

Keywords: cement-based; extrusion; phase change material; thermal energy storage; thermal insulation

18 Li and Li

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INTRODUCTION

With the growing energy crisis and environmental concerns there is an urgent need to search for new and renewable energy sources and use energy more efficiently and rationally. In civil engineering, thermal insulation and heat storage of building materials are becoming increasingly attractive because they are as important as developing new sources of energy. They provide the potential to attain energy savings, which will result in long-term benefit of reducing the cost of cooling as well as reducing the pollution of the environment due to heavy use of fossil fuels. And building materials produced by extrusion technique offer a number of benefits over the materials currently used for building components. The material shape is not limited to flat sheets. Instead, a variety of cross sections, including open sections, can be produced. Open sections could be filled with insulating materials, thereby improving energy efficiency. Also, extruded materials are environmentally friendly because that extrusion machinery produces little pollution. In conventional manufacturing methods, short discontinuous fibers cannot be effectively used due to some technical difficulties, such as fiber dispersion and alignment. However, development of fiber-reinforced cement composites using extrusion technique can solve these difficulties. The reason is that extrusion process can easily incorporate a relatively large volume of fibers and make them aligned in the designed direction through a die design technique. It has been proved that both static and dynamic properties of fiber-reinforced cement composites can be significantly improved, such as tensile strength, toughness and impact resistance.

Building materials incorporated with porous materials such as expanded perlite, plastic foam have been used for long time. These porous materials have interconnected pore structure and they are chemical stable. In addition, they are cheap and have abundant resource. Generally, they are used to produce lightweight building components with relatively good insulation ability since they have very low density and small thermal conductivity. But building materials containing porous materials do not always present sufficient thermal inertia. The reason is that these materials do not have large heat capacity. However, the effect of the thermal inertia is very useful especially in commercial buildings. Retard of heat wave caused by this effect would mean a decrease in the electrical consumption due to air conditioning (Cabeza et al. 2007). Particularly, in extremely cold/hot areas, electrical energy consumption varies greatly during the day and the night partly due to domestic space heating/cooling. Such variation leads to a peak load period and an off-peak period (usually between midnight and early morning). In order to level the electrical load, a differential pricing policy has been implemented in many cities in China. If the thermal energy is provided and stored during the night and then released to the indoor ambient during the day, part or all peak loads can shifted to off-peak period. Thus, effective energy consumption and economic benefit are achieved.

A solution to solve this problem is application of thermal energy storage in buildings. The thermal energy storage may be in the form of sensible heat, latent heat etc. For sensible heat storage, heavy material mass is needed. By comparison, latent heat storage is preferred due to the large energy storage density and nearly isothermal nature of the storage process during which the storage material, phase change material (PCM), undergoes a change in phase. Phase change materials use chemical bonds to store and release the heat. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. PCMs can be classified into two major categories: inorganic compounds and organic compounds. Inorganic PCMs include salt hydrates, salts, metals and alloys, whereas organic PCMs are comprised of paraffin, fatty acids and polyalcohols. Paraffin is taken as the most promising phase change material because it has a large latent heat and low cost and is stable, nontoxic and not corrosive (Khudhair and Farid 2004).

Over the past decades, extensive research work on the incorporation of PCMs into building envelopes to achieve latent heat storage has been done, and can be found in the literature. Several forms of bulk encapsulated PCM has been marketed for active and passive solar applications. Basically PCMs are used in building components and heat or cold storage units. Building components such as wallboards, shutter, concrete blocks, floors and ceiling boards impregnated with PCM have been proven to be successful. After Kedl and Stovall (1989) presented the concept of octadecane wax impregnated wallboard, wallboards filled with wax by using immersion process has been successfully scaled up from small samples to full size sheets. Neeper (2000) has examined the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes as PCMs that are subjected to the diurnal variation of room temperature. Lee et al. (2000) have studied and presented the results of macro-scale tests that compare the thermal storage performance of ordinary concrete blocks with those that have been impregnated with two types of PCMs. Farid and Kong (2001) have constructed two concrete slabs, one of them containing encapsulated PCM. The performances of the two concrete slabs were tested experimentally and compared with each other. The thermal mass of the concrete was increased significantly by imbedding the PCM nodules.

Containment costs and attendant problems have been major problems with many of the PCM systems developed in the past. Until now, existing methods for encapsulating PCM in building materials include direct incorporation and immersion methods. The first method incorporates PCM during fabrication process of building materials. The second method incorporates PCM into building materials by means of natural immersion. These two methods are simple and easy to use. However, their incorporation quantity of PCM in porous materials is small, resulting in low thermal energy storage level.

In this study, a simple mixing method (Siu W L 2000) and vacuum impregnation method (Zhang Dong et al. 2005) were used to make granular phase change composites. And two types of samples incorporated with paraffin and granular phase change composites have been manufactured by extrusion technique and thermal behavior of them has been investigated by using two kinds of tests, heat capacity test and simulated room test.

EXPERIMENTAL

Materials

Paraffin wax with melting point of 43°C was used as phase change material. The paraffin is a waxy crystalline substance that is white, odorless and translucent. It is obtained from petroleum by distillation. Porous material used was expanded perlite. Perlite is a lightweight cellular aggregate formed by heating the crushed natural volcanic mineral. It is the commonly used lightweight aggregate or a loose filler material to produce lightweight concrete or cement composites for fire-resistant insulation or fire protection. They are in the form of particles and have well interconnected pore structures. The perlite used in this study had a bulk density of 160kg/m³ with a thermal conduction coefficient of 0.050w/mk and water absorption volume ratio of about 50%.

Type I samples using mixing method

The procedures for paraffin being incorporated are as follows. At first, the paraffin was melted and maintained at the liquid state. The silica sands that had been heated previously were put in the liquid paraffin. Then the sands and paraffin were continuously mixed until the paraffin uniformly coated on the particle surface. This was the means of incorporation for type I samples.

After silica sands coated with paraffin were ready, the next step for extrusion was to make cementitious slurry. The cementitious slurry was prepared in advance to disperse the short PVA fiber uniformly. The slurry was formed by using cement and slag. When slurry was ready, the PVA fiber was mixed with the slurry for about 3 minutes. After that, all other materials that had been premixed for 3 minutes previously were added and followed by 3 minutes of mixing process. The finally mixed dough-like fresh cementitious materials were fed into the chamber of a single screw vacuum extruder (PVL100.3, KEMA). After further mixing, de-airing, and compacting in the extruder, the composites were extruded out through a rectangular die with cross sectional area of 300mm×20mm. The extrudate were cured under plastic covers for 24h, and then they were placed into a high temperature (50°C) and high humidity (99%) environment and cured for 3 days. After curing, the extrudates were cut into 300mm×300mm×20mm panels for testing. Surface treatment is necessary for avoiding leakage of paraffin during tests. Before tests, the density of samples was measured. It is around 2400kg/m³.

Type II samples using vacuum impregnation method

The expanded perlite was placed inside a flask, which was connected to a vacuum pump, vacuum meter and a container of paraffin. The air in the flask was evacuated by the vacuum pump and the pressure inside the flask can be monitored by the vacuum meter. In this study, the evacuation process continued for about 30 minutes at vacuum pressure of 88.1kpa. It was expected that the air in pores of perlite was evacuated during this period. After evacuation process, the valve of container was turned open to allow the PCM liquid to enter into the flask. The amount of PCM was enough to cover all the perlite. Then air came into the flask and forced the PCM liquid to penetrate into the pores of perlite. The perlite was immersed in paraffin liquid for 30mins. The flask was heated to make sure that the

temperature of paraffin did not drop too much. After immersion, the perlite filled with paraffin was taken out of the flask and cleaned with dry towel. They were placed onto a steel mesh to avoid sticking together during cooling of paraffin. After cooling, granular phase change composites were ready to be used as aggregates. Even with more paraffin were expected to be incorporated inside the pores of perlite, it was unavoidable that a thin film of paraffin was coated on surface of perlite particles because of immersion. So these samples, compared with pure perlite particles, were hard enough to resist damage during mixing and extrusion process.

The extrusion process is the same as what presented in above section. The samples for testing were also cut into 300mm×300mm×20mm panels. Since large amount of perlite was incorporated, the unit weight of panels was around 1700kg/m³.

Characterization of expanded perlite, paraffin and granular phase change composites

The chemical composition of the perlite was determined by means of X-ray fluorescence spectrometry (XRF). Pore size distribution of the expanded perlite was measured by using Mercury Intrusion Porosimetry (MIP). Microstructures of expanded perlite and granular phase change composite were observed using a scanning electron microscope (SEM). The phase change temperature and latent heat of the paraffin and the composite were measured by using a differential scanning calorimeter (DSC), and the rate of raising the temperature was 5°C/min.

Test of thermal performance of panels made with granular phase change composites

Thermal capacity test--Experimental study of the thermal capacity was conducted by using the Controlled-Environment Multi-Test Facility (Dept. of Mechanical Engineering, HKUST). Basically, there are three main parts in the facility, namely indoor room, outdoor room, and control panel. The indoor and outdoor rooms are separated by a thermal-insulating partition wall, which has one opening at the centre. The sample can be fixed inside a thermal insulating holder. The holder is then fitted into the opening of the separating partition wall (Figure. 1). Then it is expected that the heat exchange between indoor and outdoor room mainly through the specimen tested. This facility can be used to simulate an indoor and outdoor environment and measure the thermal properties of the materials fixed at the opening. The size of the rooms is approximately 60 m³. The temperature of the outdoor room is set to be able to vary from -10 to 60 °C while that of the indoor room is from 5 to 40 °C. The temperature of both rooms can be adjusted with accuracy of ±0.1 °C through operation of the control panel. In addition, temperatures at some target locations can be measured by thermal-sensors connected to the control panel.

In this test, the target temperatures of both indoor and outdoor rooms were set to 21°C. The room temperatures gradually changed and finally reached a steady state in which temperatures of indoor and outdoor room are 21°C. After that, the controls of both rooms were turned off. This means that the temperatures of both indoor and outdoor rooms were free to change. Then an infrared lamp was used as a heating device at the outdoor side (Figure.1). The lamp was placed at 300mm from the surface of the sample. The light beams should project on the sample to heat it up. It attempted to simulate a situation in which a certain heat source directly radiated on the sample. Under such condition, the variation of the indoor room temperature could be examined by using thermal sensors. Finally, the thermal insulation performance could be evaluated by considering the change of the air temperature at the indoor side.

Simulated room test--The experimental setup consisted of two identically shaped cubicles made with two types of samples. One of them used expanded perlite as aggregate and the other used granular phase change composites. Mix proportion is listed in [Table 2](#). In order to make fair comparison of the results between them valid, volumes of expanded perlite and granular phase change composites used in the panels are the same. The volume ratio of them in the panels is 30%. So the only difference is that one of them used paraffin wax. These two cubicles were placed into a thermal chamber which can simulate variation of temperatures. And the cubicles were instrumented with thermal couples then the temperatures inside them were continuously monitored during the described time.

RESULTS AND DISCUSSIONS

Pore size distribution and absorbability of expanded perlite

In order to investigate the absorbability of the expanded perlite, pore size distribution of it was measured by MIP. The pore size distribution of the expanded perlite is shown in [Fig. 2](#). It can be seen from the figure that the diameter of pores in perlite is around 80 μ m. Microstructures of perlite and granular phase change composites were shown in [Fig. 3](#) and [Fig. 4](#). It can be seen that much paraffin got into pores of perlite which made microstructure of perlite loaded with paraffin looks very different from that of perlite.

An easy way to determine how much paraffin was absorbed by perlite is to measure mass of perlite and mass of granular phase change composites made by same volume of perlite. But because it is unavoidable that paraffin sticks around the perlite during immersion, increase of volume caused by coated paraffin has to be taken into consideration. So sieving analysis of perlite and granular phase change composite was done to determine how much of them coated. The result shows that the average diameter of granular phase change composite is larger than that of perlite. It is confirmed that the volume of perlite increased after immersion. Then mass of perlite and granular phase change composite made with same volume of perlite were measured. It was determined that perlite of 1 gram can absorb 4 gram paraffin. It means that mass fraction of paraffin in the granular phase change composites is 80%.

Thermal characteristics of granular phase change composites

[Fig. 5](#) shows the DSC curves of the pure paraffin used in the production of the composites. These DSC curves present reference data to evaluate the changes in the thermal properties of the granular phase change composites, depending on the amount of paraffin. In [Fig. 5](#), the main peak represents the solid-liquid phase change of the paraffin and the melting temperature is 43.37°C. [Fig. 6](#) shows the DSC curve of granular phase change composites. There is also one main peak and the thermal characteristics of the composite are very close to the pure paraffin because no chemical reaction happened between the paraffin and perlite in the process of vacuum impregnation. The latent heat obtained in DSC tests of solid-liquid transition of pure paraffin is 133.6348J/g and that of the composites is 108.4609J/g. Then we can get the mass ratio of paraffin in the composites is 81% (108.4609/133.6348). This ratio is the same as what we got earlier.

Thermal behavior of panels made with paraffin and composites

Thermal performance of panels incorporated with paraffin--In this test, the infrared lamp was used to heat the sample face at the outdoor side. The purpose of experiment is to investigate the PCM's effect when phase change occurs.

As the initial condition was 21°C, the air temperature started to rise, as shown in Figure 7. By considering the different paraffin contents in type I material, the air temperature rises most rapidly for the type I sample with no paraffin, (I-R). The type I sample with 1% paraffin, I-1, shows decrement of air temperature and that with 2% paraffin content leads to the lowest air temperature among type I materials. This means the indoor temperature can be reduced and controlled by adding certain amount of paraffin into wall panel. Also it was found in Figure 7 that thermal inertia of samples was improved by incorporation of paraffin. Temperature development of samples incorporated with paraffin was slower than that of samples without paraffin. For example, time needed to reach 25 °C for samples with 2 paraffin were all longer than 200 minutes, but that needed to reached 25 °C for samples without paraffin were shorter than 160 minutes.

Thermal performance of panels incorporated with granular phase change composites--Fig. 8 shows the variation of temperatures inside the cubicles made with panels that use pure perlite and granular phase change composites, respectively. There are 3 thermal cycles in the tests. One cycle is that the ambient temperatures inside the chamber rise from 20°C to 60°C then fall from 60°C to 20°C both at rate of 0.5°C/min. From these figures, three points can be highlighted: the first is the cubicle without paraffin has a maximum temperature 3°C higher than that with paraffin; the second is the maximum temperature with paraffin appears about 40 mins delayed than that without paraffin, that is, the thermal inertia of the panel is higher; the third is this thermal inertia appears again due to transformation of paraffin from liquid to solid state when temperature falls.

CONCLUSIONS

Thermal behaviors of granular phase change composites produced by vacuum impregnation method and panels made with this composite are presented in this study. It can be found that heat capacity of samples increased after incorporation of phase change materials. It is also demonstrated that the vacuum impregnation method is successful and effective in production of granular phase change composites and thermal inertia of construction materials made with the composites improved due to effective incorporation of phase change materials.

ACKNOWLEDGEMENT

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Unit conversion:**1 inch = 25.4mm****1 pcf =16 kg/m³** **$T(^{\circ}\text{F})=1.8\times T(^{\circ}\text{C})+32$**

Table 1: Mixing Proportions of type I samples

Type	Sample No.	Matrix	Paraffin	Aggregate	W/C	ADVA	MC	V _f
I	I-R	C+SL	-	SS1+SS2	0.28	0.025%	1%	2%
	I-1	C+SL	1%	SS1+SS2	0.28	0.025%	1%	2%
	I-2	C+SL	2%	SS1+SS2	0.28	0.025%	1%	2%

Note: Matrix, C: cement; SL: slag; SS1 and SS2: 600-300µm and 150-90µm silica sand, respectively; ADVA: superplasticizer; MC (Methocel): rheology enhancing agent; V_f: PVA fiber volume ratio; PVA: polyvinyl alcohol fiber; W/C means water to cementitious materials ratio; I-R means the reference material for type I and the following number means paraffin content, e.g. II-1 represents type II material, i.e. 30% foam plastic, with 1% paraffin

Table 2--Mix formulation of the type II samples

Type	Cement	Fly Ash	Perlite (Composites)	PVA	ADVA	PAM	W/B
II	0.75	0.25	0.3	2%	0.025%	1%	0.28

Note: PVA: Polyvinyl Alcohol fiber; B: binder (cement + fly ash); W: water; Composites: granular phase change composites; ADVA: superplasticizer; PAM: rheology enhancing agent. Perlite, Granular phase change composites and PVA fibers are presented in the volume ratio;

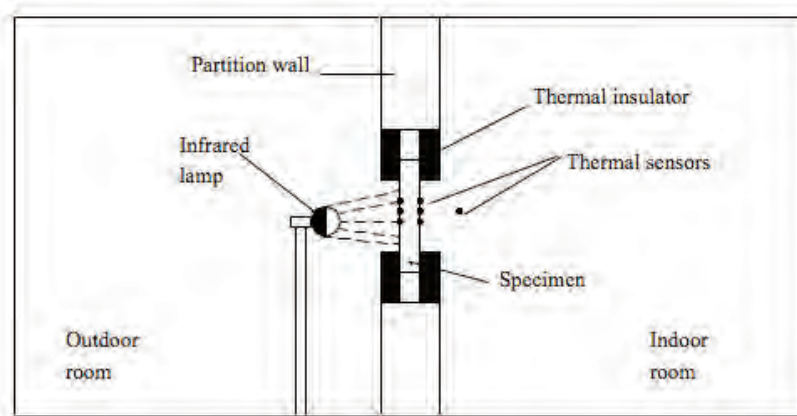


Fig. 1--Experimental arrangement of thermal capacity test using infrared-lamp as heat source.

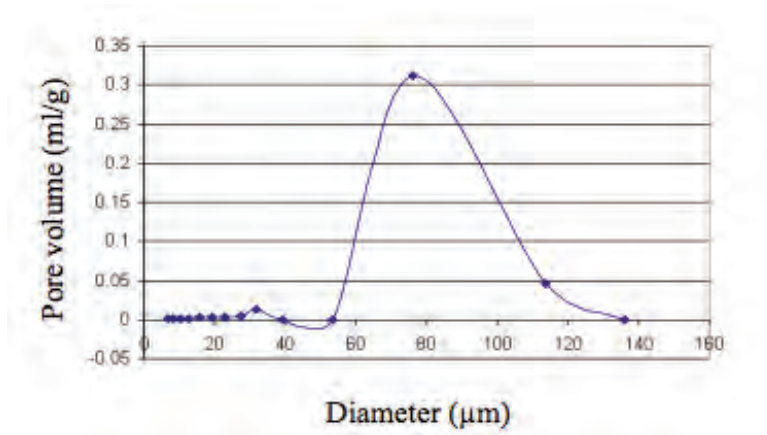


Fig. 2--Pore size distribution of expanded perlite (1 inch = 25.4mm).

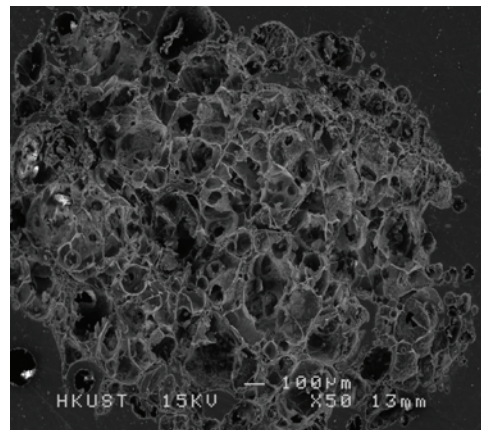


Fig. 3--Microscopic image of as-received perlite.

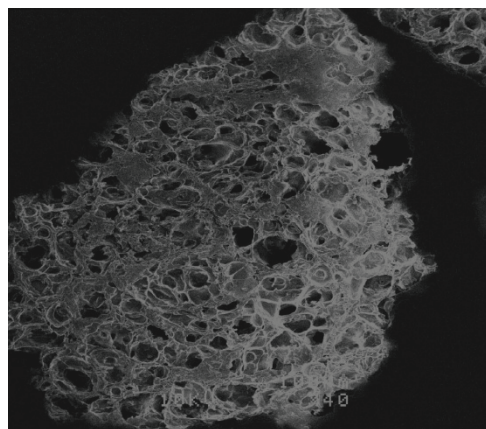


Fig. 4--Microscopic image of granular phase change composites (paraffin impregnated).

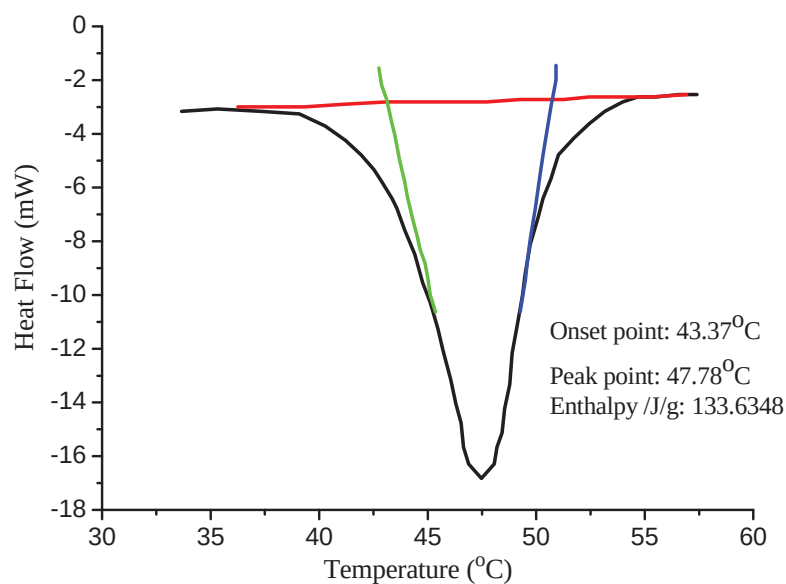


Fig. 5--DSC curve of pure paraffin.

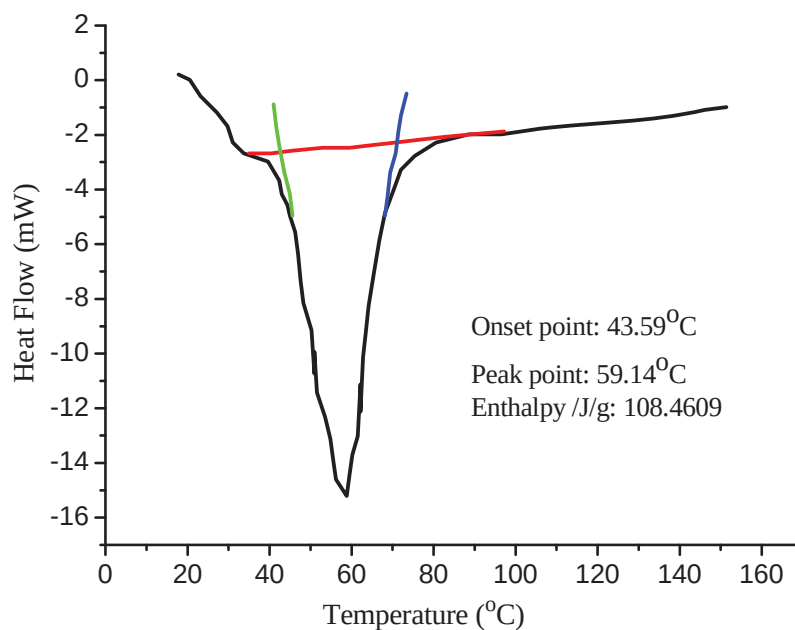


Fig. 6--DSC curve of granular phase change composites.

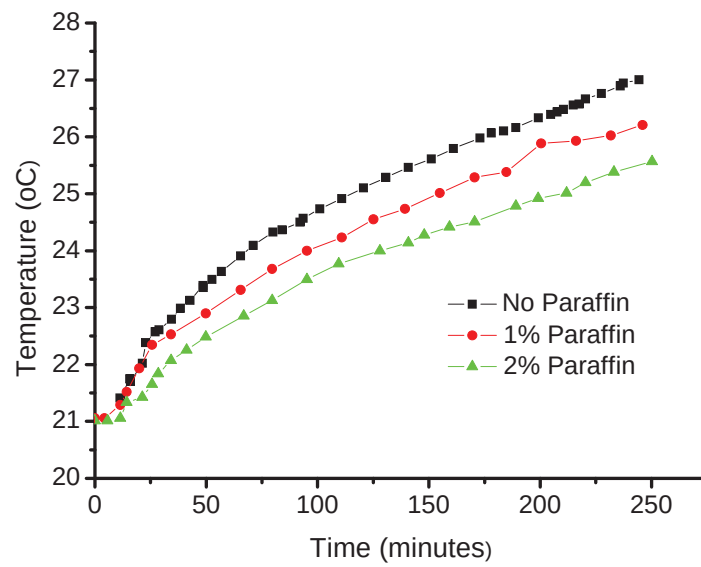


Fig. 7--Air temperature at 75 mm from the cold surface of the type I samples with 0, 1, and 2% paraffin.

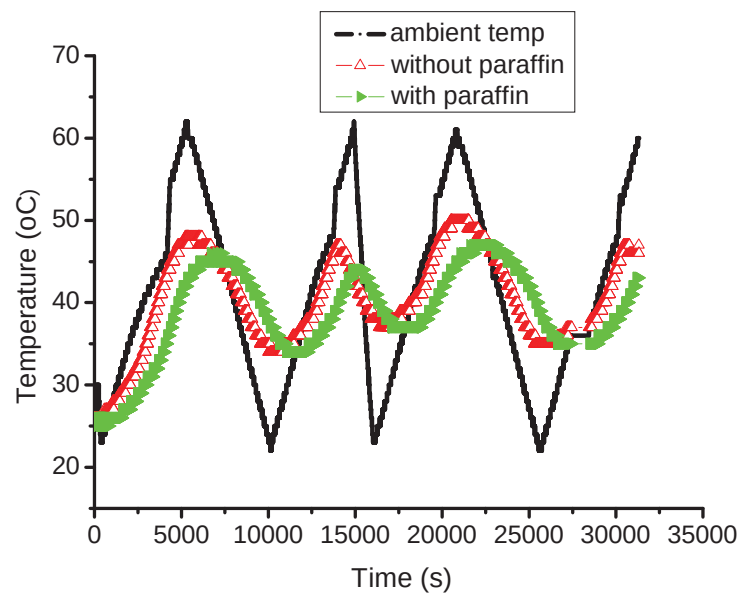


Fig. 8--Thermal behavior of cubicles made with type II samples.

Nailable Extruded HPFRCC for Use in Residential Building Applications

by K.G. Kuder and S.P. Shah

Synopsis: Extruded high-performance fiber-reinforced cementitious composites (HPFRCC) offer a number of benefits over the materials currently used in residential construction, including improved strength, ductility and durability, increased design flexibility, improved safety in the event of natural hazards and greater affordability. Despite these benefits, the use of extruded HPFRCC is not widespread in North America. Current extruded HPFRCC are difficult to nail, requiring excessive force to nail and often cracking due to nailing stresses. Research at the Center for Advanced Cement-Based Materials (ACBM), headquartered at Northwestern University, has focused on developing nailable extruded composites. Using a previously developed test method, the nailing performance of extruded HPFRCC was evaluated and compared with commercial products. Existing cavity expansion- and fracture mechanics- based models were used to determine the material parameters required for nailing. The results indicate that by tailoring both the matrix and the fiber reinforcement, nailable extruded composites can be produced. Nailable extruded HPFRCC have a reasonably low density and compressive strength (to allow for nail penetration) and a high fracture toughness (to resist cracking due the nailing stresses).

Keywords: cavity expansion; extrusion; fracture mechanics; nailing

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INTRODUCTION

Currently, homes in North America are constructed with a variety of wood-, metal-, polymeric- and cement- based systems. However, a number of concerns exist with these composites. Durability issues can be significant, including fire resistance, resistance to water intrusion (resulting in freeze-thaw damage, mold and wood rot), vulnerability to termite infestation, radiation and rust¹⁻⁴. Furthermore, the use of wood-based materials in residential construction contributes to deforestation. This work seeks to contribute to the development of extruded high-performance fiber-reinforced cementitious composites (HPFRCC) for use in residential construction. These composites can be designed to be durable, environmentally-friendly and cost-competitive.

Extrusion is an advanced processing technique that can be used to produce HPFRCC. These materials exhibit a strain hardening response under tensile loading, with a tensile strength and strain capacity that is superior to conventional fiber-reinforced materials. Researchers have demonstrated that this high performance can be achieved in a variety of ways, including using micromechanical modeling⁵, tailored fiber geometries⁶ and advanced processing techniques⁷⁻¹¹.

In extrusion, a stiff cementitious dough is forced through a die of desired cross-section using either an auger or a ram. During this process, the material is subjected to high compressive and shear forces, which densify the matrix, improve the fiber-matrix bond and align fibers in the direction of extrusion^{9, 12-15}. As a result, the mechanical performance and durability of the composites are superior to similar cast materials^{10, 13}.

Extruded materials offer a number of benefits over the materials currently used in residential construction. 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, may be produced, depending on the intended use. Open sections can be filled with insulating materials, 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 can be incorporated into the material without compromising strength or ductility. Due to the increased strength and ductility of extruded materials, they offer a higher level of safety in the event of a natural hazard, such as hail or wind storms. Finally, extruded materials can be more cost effective than conventional building materials. Machinery costs are less than many setups, including the Hatschek machine, which is currently used for 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 the many advantages of using extruded HPFRCC in residential applications, their use is still not widespread in North America. One major reason that these composites have not been adopted by the housing market is their constructability. Specifically, extruded HPFRCC are difficult to nail. In the presented work, the nailability of extruded HPFRCC is examined. The material parameters required for nailability are determined using cavity expansion- and fracture mechanics- and based models. The results indicate that by properly tailoring both the matrix and the fiber reinforcement, nailable extruded HPFRCC can be produced. Nailable composites have a low density and compressive strength (to allow for nail penetration) and a high toughness (to control cracking). Additionally, nailable composites should have nail holding ability. However, since this property is dependent on the substrate involved, it was not considered in the present study.

EXPERIMENTAL EVALUATION OF NAILING PERFORMANCE

Nailing parameters

Nailing performance was evaluated using a test method developed previously¹⁶. Specimens measuring 50.4 x 177.6 x 8 mm were nailed using a Charpy impact setup, shown in [Figure 1](#), that was designed to simulate field nailing. Nailability was determined using two criteria: ease of nailing and resistance to cracking. Ease of nailing was defined as the dynamic load required for a nail (flat tipped, 3 mm diameter) to be driven through the specimen. Resistance to cracking was evaluated after the dynamic nailing test. The flexural capacity of the specimens that had been nailed was evaluated and compared to specimens that had not been nailed. The residual flexural load was calculated as:

$$F_{\text{residual}} = \frac{F_{\text{nailed}}}{F_{\text{unnailed}}} * 100 \quad (1)$$

Where F_{residual} is the residual flexural load (%), F_{nailed} and F_{unnailed} is the maximum force sustained during three-point bending for a specimen that has been nailed and not nailed (control), respectively. The greater the residual flexural load, the higher the resistance to cracking. Note that since the cross sectional area of the section changes due to nailing (material removed due to nail penetration) loads are considered, not stresses.

To be nailable, specimens should have a reasonably low nailing load (to allow for nail penetration) and a high residual load (to resist cracking). Nail holding ability is also important. However, since this property will depend on the substrate used, it was not considered in this work.

Materials

The nailing performance of laboratory-produced extruded HPFRCC was evaluated and compared with commercially-available building materials. Details about production of the extruded composites are given elsewhere and are only summarized here^{16, 17}. The matrix consisted of 30% Class F fly ash, 13% cement, 11% silica fume, 39% water, 1% high-range-water-reducing admixture (superplasticizer), 1% hydroxypropyl methylcellulose and 5% fibers (except in the case of PVA where higher fiber dosages caused clumping, limiting the reinforcement to 2%), by volume. Unreinforced and singly-reinforced cellulose, glass, polypropylene (PP) and polyvinyl alcohol (PVA) composites were produced. The properties of the fibers are given in [Table 1](#).

Four commonly-used commercial materials that are known to be nailable were also examined: two cement-based and two engineered wood. The cement-based materials were Durock® and Hardie. Durock® is a tile backerboard produced by USG that consists of a light cementitious core sandwiched between glass fiber mesh. Hardie is a Hatschek-produced, cellulose fiber-reinforced cement board that is manufactured by James Hardie for siding and backerboard applications. Hardie contains about 30% cellulose fibers, by volume, and is laminated. The engineered wood composites were oriented strand board (OSB) and plywood. The plywood used here is a three-ply plywood with an American Plywood Association rating of B-C, Group 1, exterior 221, PSI-95 underlayment. Commercial specimens were selected such that the thicknesses were as close as possible to the 8 mm thickness of the lab-produced extruded composites, with nominal thickness of 8, 8, 6.35 and 8.7 mm (0.31, 0.31, 0.25 and 0.34 in) for the Durock®, Hardie, OSB and plywood, respectively.

Results

The failure modes for the extruded and commercial materials are shown in [Figure 2](#) and [Figure 3](#), respectively. A variety of different failure modes were observed for the extruded and commercial materials: (1) penetration, (2) scabbing, (3) radial cracking and (4) complete material separation (breaking). These failure modes are ordered based on preferred failure mode, with the penetration mode being the best (as with the commercial composites), followed by a scabbing type of failure, then radial cracking and finally, the broken composites. This order is based on minimizing damage. According to this classification, the glass and PP composites have the most desirable failure modes of the extruded composites.

Results for the two nailing parameters, ease of nailing and resistance to cracking, are presented in [Figure 4](#) and [Figure 5](#), respectively. When considering only the cement-based composites, the dynamic nailing loads of the extruded composites are approximately 50% higher than the commercial products, suggesting that a reduction in the

nailing load is required. For the extruded composites, only the PP and glass composites have a residual flexural load after dynamic nailing (the plain, cellulose and PVA composites break) and these residual loads are similar to the loads of the commercial materials.

MODELING NAILING PERFORMANCE

To better understand the material parameters that govern nailing, existing cavity expansion- and fracture mechanics- based models were used. Due to the complex nature of both the nailing process and the fracture properties of HPFRCC, limitations exist with the application of these models. However, they do still provide insight into improving the nailing performance of extruded HPFRCC.

Cavity expansion modeling – the role of the matrix

Penetration mechanics was used to understand the role of the matrix on the nailing process. Cavity expansion models have been derived to analytically describe the penetration of a projectile into a concrete target. In these models, the projectile is assumed to cause ductile hole enlargement, based on either cylindrical or spherical expansion approximations. The hole is enlarged by the radial motion of the material, expanding to the diameter of the projectile. This process is similar to a nail penetrating into a cement board.

Initial cavity expansion models described the force on the projectile in terms of the projectile geometry and the triaxial behavior of the concrete. Subsequent efforts by Forrestal and colleagues led to the development of a constitutive model in which the concrete is described only by its compressive strength and density¹⁸:

$$F = \pi a^2 (S f'_c + N \rho V^2) \quad (2)$$

where the projectile is described by the radius, a , the nose shape factor, N , and the impact velocity, V . The target concrete has a density, ρ , and a compressive strength, f'_c . S is a dimensionless empirical constant. This relationship only applies when the penetration depth is greater than $4a$. When the penetration depth is less than $4a$, surface-cratering can dominate the response. Experimental data was obtained for a variety of data sets and data-fitting was then used to determine the value of S , which was found to be equal to $82.6 f'_c{}^{-0.544}$. This model assumes that the impact of the projectile is normal to the target material, that the projectile does not deform and that flexural failure is not dominant. In addition, the empirical relationship was derived using velocities ranging from 250-800 m/s (820-2,625 ft/s), which are higher than the nailing speed used in this work, although not higher than the velocities of the pneumatic nail guns used in the field. The model was also developed for concrete targets, not fiber-reinforced cementitious composites.

This work assumes that Equation (2) can be used to evaluate the nailing load of the extruded composites, provided that flexural failure mechanisms are not dominant. This relationship suggests a material will have a higher ease of nailing if the density or compressive strength is reduced. Based on this analysis, it was determined that lightweight composites could have a good nailing performance.

Fracture mechanics modeling – the role of the fiber reinforcement

The effect of the fiber reinforcement on nailing performance was investigated using three existing fracture mechanics modeling techniques: R-curves, brittleness indices and micromechanical models. It is hypothesized that the fracture toughness of these strain-hardening materials play an important role in nailability. As the nail is driven (penetrated) into the material, cracking will occur. With a sufficient fracture toughness, damage due to cracking will be minimized and, therefore, the residual flexural loads will be higher. R-Curves and brittleness indices were analyzed to evaluate the role of the fiber reinforcement on the peak load and a micromechanical model was used to evaluate the influence of the fibers on strain hardening.

R-Curves and brittleness indices -- R-curves and the brittleness index were used to evaluate the influence of the fiber until the peak load is reached. These approaches assume that the material is homogeneous and that failure occurs due to the propagation of a single crack, at which point microcracks coalesce to form a macrocrack. However, it is known that the failure mechanisms in high performance materials are quite complex, with a variety of toughening mechanisms, including fiber crack bridging, interfacial bonding and frictional slide.

Fracture parameters were determined according to the Jenq-Shah two-parameter model, which describes fracture using two geometry-independent parameters, the critical stress intensity factor, K_{IC} , and the critical crack tip opening displacement, $CTOD_c$ ¹⁹. Double-edge-notched tension specimens were loaded and unloaded in crack-mouth-opening displacement control. More details about the analysis are given in¹⁷. Due to the brittle nature of the plain composites (making it hard to mechanically secure the specimens before testing) and the quick yielding of the PP composites (causing it to be difficult to obtain the unloading compliance at the peak load), the fracture parameters of these composites could not be determined.

Fracture resistance, R-curves, were obtained using the approach proposed by Ouyang and colleagues, in which experimentally-determined fracture parameters are used to generate R-curves by solving a series of differential equations^{20, 21}.

Figure 6 presents the R-curves for the glass, cellulose and PVA composites and suggests that the glass fiber-reinforced composite has the highest fracture toughness.

Brittleness indices were also used to evaluate fracture toughening. Jenq and Shah proposed a brittleness index, Q , given by¹⁹:

$$Q = \left(\frac{E * CTOD_c}{K_{IC}} \right)^2 \quad (3)$$

Where E is the elastic modulus. This index gives an indication of the size of the fracture process zone. The larger the value of Q , the more ductile a composite is. Typical ranges for Q are 12.5-50 mm (0.5-1.97 in) for cement paste, 50-150 mm (1.97-5.91 in) for mortar and 150-350 mm (5.91-13.78 in) for concrete²². **Table 2** presents the brittleness indices obtained and, similar to the R-curve analysis, indicates that the glass fiber-reinforced composite has a higher fracture toughness than the PP or PVA composites.

Micromechanical modeling -- The influence of the fiber reinforcement on post-peak performance was analyzed using a micromechanical model developed by Li and colleagues that describes the critical volume fraction, $V_{critical}$, needed in aligned fiber-reinforced cementitious composites for strain hardening²³:

$$V_{critical} = \frac{6d_f^2 E_f}{\tau^2 L_f^3 (1 + \eta)} J_{tip} \quad (4)$$

with:

$$\eta = \frac{V_f E_f}{V_m E_m} \quad (5)$$

$$J_{tip} \approx \frac{K_m^2}{E_m} \quad (6)$$

where d_f is the diameter of the fiber, L_f is the length of the fiber, τ is the interfacial shear stress, J_{tip} is the crack tip toughness, E_f and E_m are the moduli of the fiber and matrix, respectively, V_f and V_m are the volume fractions of the fiber and matrix, respectively, and K_m is the matrix fracture toughness. This model assumes that the fiber-matrix interface can be characterized by the following: fibers do not break, the interfacial friction between the fiber and the matrix is constant and fibers completely debond and pullout of the matrix.

The critical volume fraction of fiber reinforcement required for strain hardening was calculated for the extruded composites using equation (4). The fiber properties are given in **Table 1**. Akkaya and colleagues had determined that the matrix fracture toughness, K_m , for a similar mix design was 26 MPa*mm^{1/2} (0.75 ksi*in^{1/2})¹⁵. E_m was approximated as 14.85 GPa (2,146.6 ksi), corresponding to the modulus determined from the flexural testing of the plain composites. Values for the interfacial shear strength were obtained from the literature and are given in **Table 3**. No value could be found for the interfacial properties of cellulose fiber. Therefore, the critical volume fraction was not obtained for these composites.

The results from the micromechanical analysis are provided in [Table 3](#) and suggest that the glass and PP fiber-reinforced composites have enough fiber reinforcement to undergo strain-hardening. According to Equation (4), reducing the crack tip toughness, J_{tip} , lowers the critical volume fraction of fibers that is needed to achieve multiple cracking. Thus, a reduction in the modulus or fracture toughness of the matrix should improve the strain hardening response of the extruded materials.

It is important to note that the values reported in the literature depend on the properties of the matrix and the fiber surface used by the authors and are, therefore, not identical to the properties of the materials used in this work. Additionally, the model makes assumptions about the fiber-matrix debonding properties, which might not be valid for all of the fibers investigated.

PRODUCTION OF NAILABLE COMPOSITES – LIGHTWEIGHT EXTRUDED PP AND GLASS FIBER-REINFORCED COMPOSITES

Based on the experimental and modeling results, lightweight extruded HPFRCC with either glass or PP fiber reinforcement were produced to obtain a nailable material. The modeling results suggest that extruded composites with either glass or PP fiber reinforcement have a greater fracture toughness than the plain or PVA fiber-reinforced composites. In the experimental part of the work, only the glass and PP composites remained intact after nailing. Thus, fracture toughness does appear to be a good indicator for nailability, and the glass and PP fiber-reinforced composites investigated have a sufficient toughness for nailing. However, the nailing load of the extruded composites is higher than the other cement-based products and, therefore, should be reduced. The cavity expansion modeling results suggest that by reducing the density and the compressive strength of the composites, resistance to penetration should be reduced. In addition, the micromechanical modeling indicates that a reduction in the elastic modulus should increase fracture toughness. Therefore, lightweight composites were produced.

Material production

Lightweight extruded HPFRCC were produced using expanded polystyrene beads (EPS). The EPS were produced by Huntsman Chemical, with a density of 0.035 g/cm^3 (0.001 lb/in^3) and had diameters that ranged from 1.4-2.2 mm (0.051-0.072 in) (EPS 1) and from 0.8-1.4 (0.029-0.051 in) (EPS 2). Composites were extruded using the same matrix as was used previously, following the same production method. Visual and microscopic investigations indicated that the EPS did undergo some damage due to extrusion, but the damage appeared to be reasonable (measured by estimating theoretical densities)¹⁷. The material properties of the glass and PP fiber-reinforced specimens containing the EPS are given in [Table 4](#) and [Table 5](#), respectively. Generally, as the amount of lightweight filler increased, the compressive strength, elastic modulus and density decreased.

Due to the compressible nature of EPS, the finished product did have a rough surface. For the smaller size beads, the damage was less. Future work could include more investigation into this issue. However, the main point of this work is to show the effect of reducing the density, compressive strength and elastic modulus on nailability.

Nailability results

The nailing performance of the lightweight glass and PP fiber-reinforced composites was evaluated using the method discussed previously. Nailable composites were achieved once a sufficient amount of lightweight filler was added. [Figure 7](#) shows an example of a nailable composite. From the exit face, only a small amount of damage is seen with the failure mechanism being primarily penetration-dominated, which is similar to the performance of the commercial products. The observed failure modes for the composites are summarized in [Figure 8](#). Generally, as the amount of EPS is increased, causing a decrease in the elastic modulus, compressive strength and density, nailability improves with failure modes transitioning to penetration-type failures.

The nailing and residual flexural loads are given for the nailable extruded composites in [Figure 9](#) and [Figure 10](#), respectively, and compared with the commercial materials. The nailing loads of the extruded composites fall within the range of the commercial products. In addition, with the exception of the EPS2 45g, the residual flexural loads of the nailable extruded materials are comparable to the commercially-available composites. These results suggest that lightweight glass or PP fiber-reinforced materials could be used in similar applications as the commercial materials.

The relationship between the resistance to penetration (Equation 2) and the dynamic nailing load for the extruded composites is shown in **Figure 11**. Both the composites with and without EPS are plotted. Only composites that remain intact after nailing are shown (i.e. the plain, cellulose and PVA are not included), since the cavity expansion relationship assumes that flexural failure is not dominant. A good relationship is observed between the resistance to penetration and the nailing load for the materials, which demonstrates the benefit of decreasing the density, compressive strength and elastic modulus of a material to enhance the ease of nailing.

CONCLUSION

The objective of this work was to determine the material parameters needed to achieve nailability. To do so, nailability criterion were defined. Composites with a good nailability should be: (1) easy to nail (low nailing load), (2) resistant to cracking (high residual flexural load) and (3) have a penetration-dominated failure. Nailable composites are shown to have a low compressive strength, elastic modulus and density and have a high fracture toughness. Based on these findings, lightweight nailable extruded HPFRCC were produced.

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Table 1--Fiber properties

Fiber	Tensile Strength MPa (ksi)	Elastic Modulus GPa (ksi)	Fiber Diameter μm (μin)	Fiber Length μm (μin)	Density kg/m^3 (lb/ft^3)
Cellulose Weyerhaeuser Kraft processed	-	-	10 - 15 (390-585)	≈ 2.5 (97.5)	-
Bundled Glass Cem-FIL 62/2	3500 (507.64)	71 (10297.84)	14 (546)	6 (234)	2680 (166.16)
Polypropylene (PP) Forta Mighty-Mono	700 (101.53)	5 (725.2)	50 (1950)	13 (507)	910 (56.42)
Polyvinyl Alcohol (PVA) Kuraray RM 182	1900 (275.58)	41 (5946.64)	14 (546)	2 (78)	1300 (80.6)

Table 2 -- Fracture parameters

	K_{IC} MPa-mm ^{1/2} (lb/in)		$CTOD_c$ mm (μin)		Q mm (μin)
	avg	stdev	avg	stdev	
Cellulose	44.07 (1262.25)	6.37 (182.4)	0.02 (623.97)	0.01 (369.41)	37.47 (1.46)
Glass	170.76 (4891.2)	35.06 (1004.18)	0.05 (1944.81)	0.02 (849.94)	64.96 (2.53)
PVA	114.84 (3289.51)	20.69 (592.5)	0.02 (623.97)	0.02 (933.67)	10.61 (0.41)

Table 3 -- Critical volume fraction for strain hardening based on micromechanics model

	τ Mpa (psi)	$V_{critical}$ %	V_{used} %
glass¹	0.69 (100.08)	2.96	5.0
PP²	0.32 (46.41)	1.50	5.0
PVA³	2.4 (348.1)	4.52	2.0

¹Li, Z., Mobasher, B. and Shah, S. P. (1991). *Journal of the American Ceramic Society*.

²Takashima, H., Miyagai, K., Hashida, T. and Li, V. C. (2003). *Engineering Fracture Mechanics*.

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Table 4 -- Material properties of glass fiber-reinforced extruded with lightweight expanded polystyrene (EPS) beads

Composite		Density g/cm ³ (lb/ft ³)	Elastic Modulus GPa (ksi)	Flexural Strength MPa (psi)	Flexural Toughness MPa-mm (lb/in)
Lightweight Filler	Volume Replacement (%)				
none	0	1.61 (100.68)	9.54 (2834.15)	31.27 (4535.57)	86.56 (489.61)
EPS1	15	1.41 (87.79)	6.4 (927.99)	22.37 (3243.86)	52.73 (298.28)
	30	1.18 (73.65)	4.96 (719.81)	18.25 (2647.24)	38.65 (218.65)
	45	1.02 (63.93)	3.33 (483.25)	9.81 (1422.43)	20.14 (113.94)
EPS2	15	1.37 (85.73)	9.67 (1401.87)	21.72 (3150.45)	54.06 (305.77)
	30	1.1 (68.39)	5.55 (804.46)	16.31 (2365.77)	37.92 (214.48)
	45	1.01 (62.98)	3.99 (578.27)	11.56 (1676.85)	20.77 (117.5)

Table 5 -- Material properties of fiber-reinforced polypropylene extruded with lightweight expanded polystyrene (EPS) beads

Composite		Density g/cm ³ (lb/ft ³)	Elastic Modulus GPa (ksi)	Flexural Strength MPa (psi)	Flexural Toughness MPa-mm (lb/in)
Lightweight Filler	Volume Replacement (%)				
none	0	1.5 (93.61)	16.04 (2327.1)	9.58 (1389.18)	94.02 (531.8)
EPS1	15	1.27 (79.33)	7.61 (1103.72)	6.87 (995.77)	63.06 (356.69)
	30	1.11 (69.54)	3.18 (461.86)	4.95 (717.41)	40.92 (231.45)
	45	0.84 (52.37)	2.96 (429)	3.68 (534.11)	35.36 (199.99)
EPS2	15	1.31 (81.75)	11.08 (1607.14)	7.69 (1114.7)	73.91 (418.06)
	30	1.17 (73.17)	2.55 (369.25)	4.72 (684.46)	44.27 (250.43)
	45	0.94 (58.47)	1.64 (238.47)	4.32 (626.77)	36.86 (208.51)

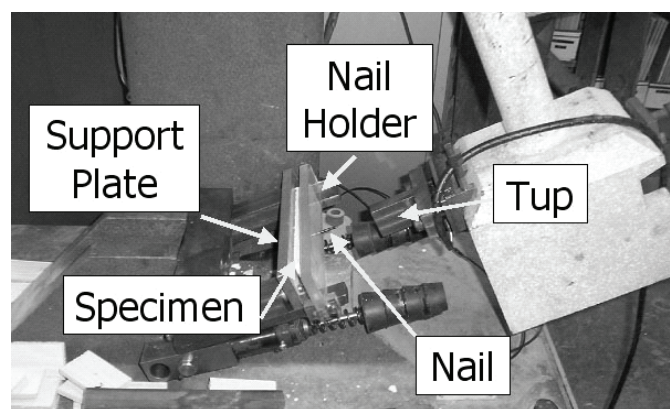


Figure 1 -- Modified Charpy impact setup.

Plain



Cellulose



Glass



PP



PVA



Figure 2-- Failure modes of extruded composites (nail exit face).

Durock



Hardie



OSB



Plywood



Figure 3 -- Failure modes of commercial composites (nail exit face).

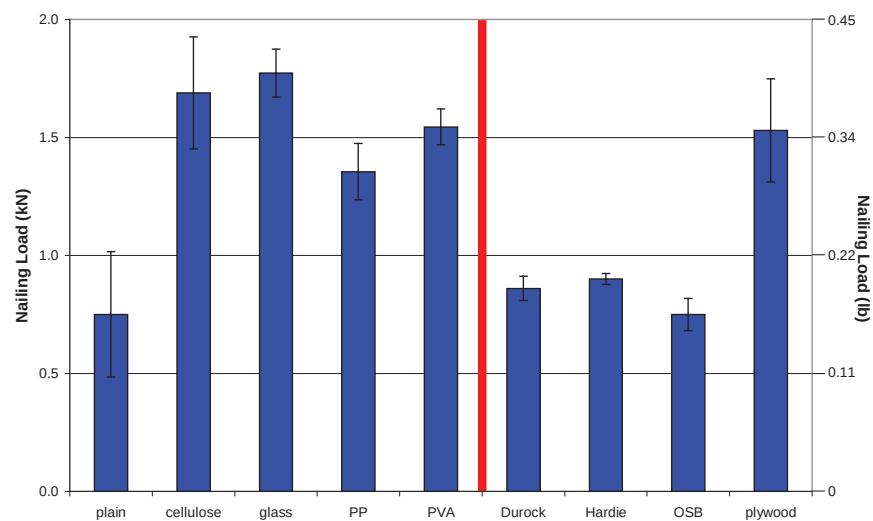


Figure 4 -- Ease of nailing - nailing load of extruded and commercial composites with standard deviations.

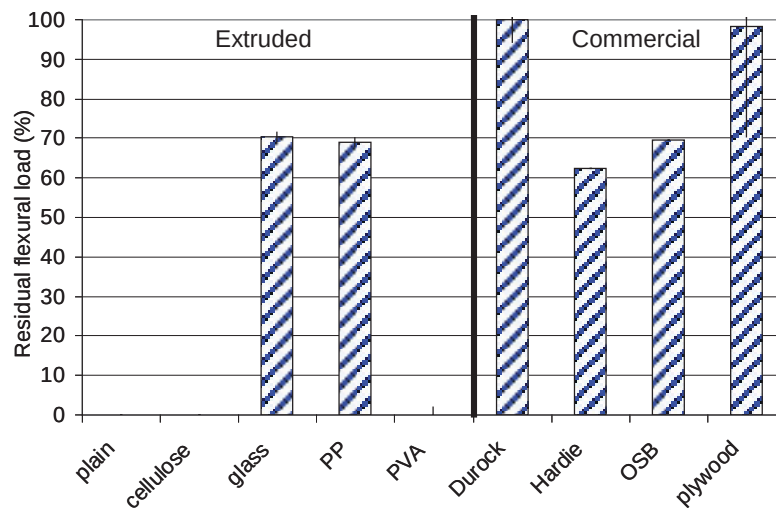


Figure 5 -- Resistance to cracking - residual flexural load of extruded and commercial composites.

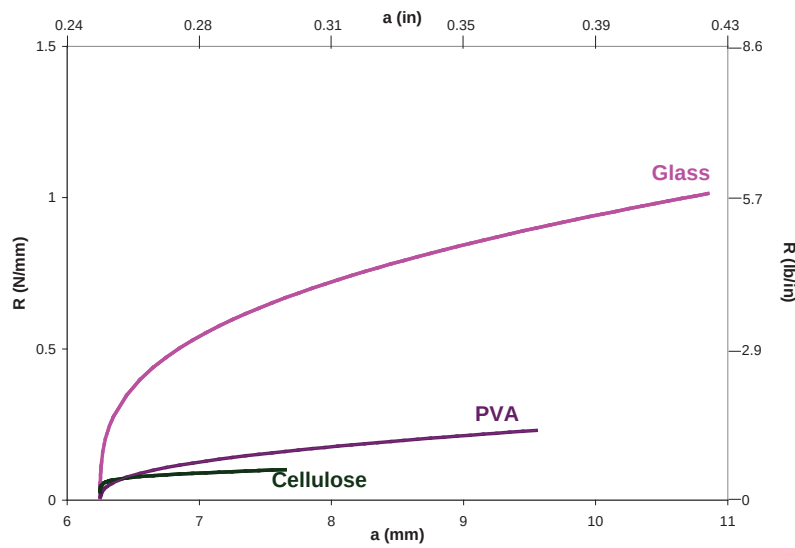


Figure 6 -- Fracture resistance, R-Curves, for extruded composites.

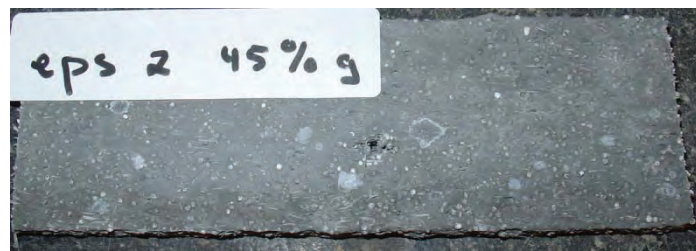


Figure 7 -- Nail exit face of extruded composites with EPS (here with glass fiber-reinforcement).



radial cracking (rc) → scabbing (s) → penetration (p)

		0	15	30	45
Glass	EPS1	s	s	p	s
	EPS2		s	s	p
PP	EPS1	rc	rc/s	rc/p	p
	EPS2		rc/s	s	p

Figure 8 -- Failure modes of extruded materials with lightweight filler.

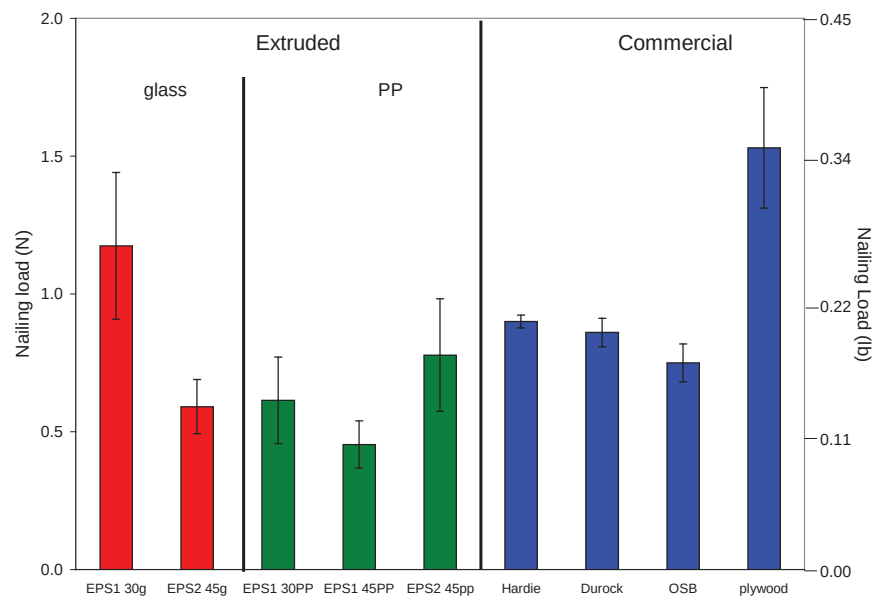


Figure 9 -- Nailing load of nailable extruded composites and commercially-available materials.