RESEARCH REPORT
External Research Program

Gypsum Wallboard Core Structure and Effects on End Use Performance

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CMHC 2006 External Research Program Final Report
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Thursday May 31, 2007

ABSTRACT

Interior grade gypsum wallboard products are manufactured by combining an aqueous pregenerated chemical foam with a plaster/water flowable slurry to form a porous lightweight core panel that contains many cellular air voids. Recent technology advances in foaming agent chemistry and manufacturing equipment have altered the traditional gypsum core structure to preferentially contain relatively large air voids as opposed to relatively small air voids. The purpose of this project is to produce lab board samples made from various industry representative chemical foaming agents, produced at various foam densities in order to generate an array of different structures to be evaluated. These samples were investigated for 2 major performance parameters; (a) Fire resistance as measured by shrinkage resistance and surface cracking when exposed to high temperatures and (b) Fastening performance as measured by nail pull testing. These results are intended to highlight any potential correlation between core structure and end-use performance. These types of core structures may then ideally be targeted by gypsum board producers to create safe and strong products for use in Canadian housing.

EXECUTIVE SUMMARY

This project is intended to produce lab board samples made from various industry representative chemical foaming agents, produced at various foam densities in order to generate an array of different structures to be evaluated. These samples were investigated for 2 major performance parameters; Fire resistance as measured by shrinkage resistance and surface cracking when exposed to high temperatures and fastening performance as measured by nail pull testing.

In general it was determined that various core structures at relatively consistent board weights were able to be produced using a lab scale continuous foam generation system. The void structures produced were characterized by high resolution computed tomography (CT) scanning which determined average void sizes ranging from 275-750 μm. Firing these samples to approximately 1000 degC over 2 hours showed no observable affect of core structure on volumetric shrinkage or surface cracking resistance. Nail pull measurements showed a degree of scatter of results that did not absolutely correlate core structure to nail pull performance but did highlight some potentially strong performing samples. Interestingly many samples generated outperformed the reference commercial sample which did not pass the ASTM/CSA standard. Likely more measurements of nail pull are required to reduce the variations that were observed for the lab board samples.

RÉSUMÉ

Le projet a pour objectif de produire des échantillons de laboratoire à partir de différents agents moussants chimiques représentatifs, comportant des densités variées de manière à créer un échantillonnage de différentes structures alvéolaires à évaluer. Ces échantillons ont été examinés pour en déterminer deux paramètres principaux : la résistance au feu mesurée en fonction de la résistance au retrait et à la fissuration superficielle, lorsqu'exposés à des températures élevées, et la performance des fixations au moyen d'essais de résistance à l'arrachement des clous.

En règle générale, on a déterminé qu'il était possible de produire différentes structures alvéolaires ayant une masse relativement uniforme au moyen d'une installation de production de mousse en continu, à l'échelle laboratoire. Les structures alvéolaires produites ont été caractérisées par balayage en tomodensitométrie haute résolution (TDM-HR) de manière à déterminer la dimension moyenne des alvéoles qui vont de 275 à 750 µm. À la suite d'une cuisson à une température d'environ 1000 °C pendant deux heures, les échantillons ne présentaient aucun effet observable sur la structure alvéolaire quant au retrait volumétrique ou à la résistance à la fissuration superficielle. Bien que les essais d'arrachement de clous présentent un niveau de dispersion qui ne permet pas d'établir de corrélation avec la structure alvéolaire, ils ont toutefois fait ressortir la forte performance de certains échantillons. Fait intéressant, de nombreux échantillons produits ont surclassé les échantillons commerciaux de référence qui ne répondent pas à la norme de l'ASTM/CSA. Il faudra sans doute davantage d'essais à l'arrachement de clous pour réduire les écarts observés dans le cas des échantillons produits à l'échelle laboratoire.

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1. Introduction

Commercial gypsum board panel products represent the most popular interior finishing surface in homes today. Gypsum boards are made of a porous microcrystalline gypsum mineral "core" that contains cellular air voids sometimes up to 50% by volume. Gypsum is used for its ability to be easily set in a desired form, along with its ability to retain chemically bound water and therefore resist fire. Cellular air voids are processed into the core during manufacture by adding aqueous pregenerated chemical foams to a flowable gypsum slurry resulting in a light weight convenient panel product. Addition of air voids to the core using foams has significant advantage over other methods of density reduction such as increased water addition. Extra water added results in a significant increase in the energy requirements to dry the boards during manufacture. The characteristic core structures that are created using various chemical foam inputs, formulations and processes can differ significantly and likely contribute to the end use performance of the boards. Two important product performance features of gypsum boards are resistance to fire and fastening strength. It is postulated that using a novel technique to describe and define examples of different core structures produced, one could correlate structure with relationships observed in fire resistance and fastening strength performance. Some other mechanical strength characteristics and end use performance features (eg. Mold growth, moisture retention) are also likely effected by changes in board core structure but are beyond the scope of this report.

2. Scope and Objectives of Research

Representative laboratory board samples will be created using different industry available chemical foams in various formulation concentrations. The foam will be generated using a lab scale continuous foam generation system which will be built outside this project but for this specific use. A short initial comparison study of the continuous foam generation system versus batch generated foam will be completed and evaluated for weight and compressive strengths. Based on formulations of promise from the cube study, board samples will be created and scanned using X-ray computed tomography, from which quantitative image analysis techniques will determine the internal core structure. Duplicate boards will be measured for both fire resistant properties and fastening strength performance. Fire resistance will be measured through dimensional stability of samples after being subject to extreme temperatures in a laboratory kiln (i.e. 2000°F for 2 hours; measured for shrinkage and degree of surface crack formation). Fastening strength will be measured by a well known industry standard test, called the Nail Pull test using a mechanical force test apparatus.

3. Development and Qualification Testing of a Continuous Foam Generation Apparatus.

Plans for a reliable lab scale continuous foam generation system are available online. This specific system may require some tuning to be applicable to making gypsum board samples but nonetheless a serviceable apparatus will be similarly assembled by Innogyps outside the costs of this project. The advantage of a continuous system is that it best allows production of reliable foam, unsubject to batchwise variations with controlled air volume input, more similar to what is used in an actual board line. A cube strength comparison study of samples made with this continuous foam generation apparatus versus batch foam generation (controlled solution volume and mechanical shear but uncontrolled air volume input) will be completed. Three foam formulations for each of the four foaming agents of consideration, run on each batch and continuous system would be ideal (24 candidates). Cubes were created in triplicate as per ASTM C472 (72 total cubes).

A continuous foam generation system was initially built as per the plan available in the paper "A Mechanical Foam-Generator For Use In Laboratories" by Fry and French. See Figure 1. This

system used an air compressor to simultaneously supply both foaming agent solution flow (through pressurizing the head of a sealed fluid vessel) and air flow. Both phases were combined in a "T" chamber which had controlled needle valve inputs used to proportion the relative composition of air/water. The foam produced by this system was found to be reasonable in bursts although the foam production was discontinuous and difficult to consistently control for both foam weight and volume of production.
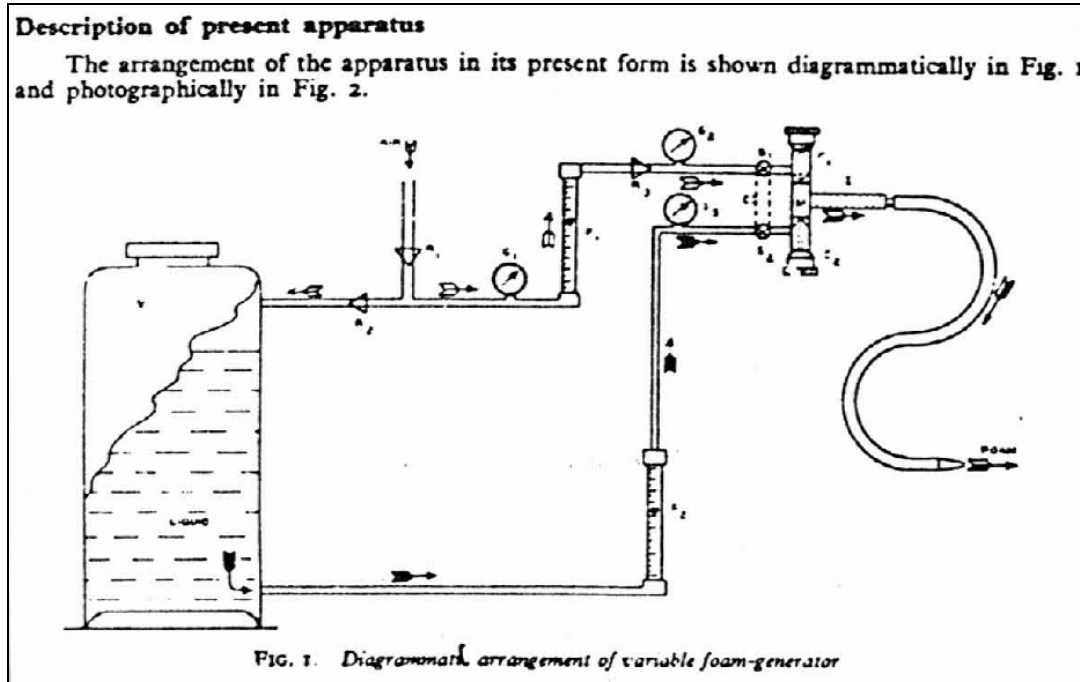

Figure 1 – Mechanical Foam-Generator Diagram

This design was abandoned and a more sophisticated system was implemented whereby the flow of both foaming agent solution and air were independently controlled and measured through indicators. A positive displacement peristaltic pump, capable of flow rates up to 1L/min, was implemented at the foaming agent solution vessel. A glass tube flowmeter with a flow control valve, capable of flow rates up to 4L/min, was used to set the volume of air input. The combination "T" chamber was altered to allow codirectional fluid flow and foam production such that foaming agent and air would combine at a surface interface ideal for bubble generation. To accomplish this, a microbubble tubing was acquired and fitted around a machined air output tube, whereby the foaming agent solution would flow through a constrained volume. Finally, to provide additional mixing capability, a 1500 RPM centrifugal pump was fitted with a neutral flow, high sheer impeller fabricated from a 4" nylon wheel brush. See Figures 2 and 3.

Overall, the redesigned system produced much more consistent foam which had both repeatable densities and repeatable production volumes. See Figure 4 for foam densities and production volumes. Note that the concentration of foaming agent solution used in cube production for each foam density was constant. This method was chosen to approximate constant foaming agent concentration with respect to the overall slurry mix. This is a consequence of the amount of water present in each foam density being variable.

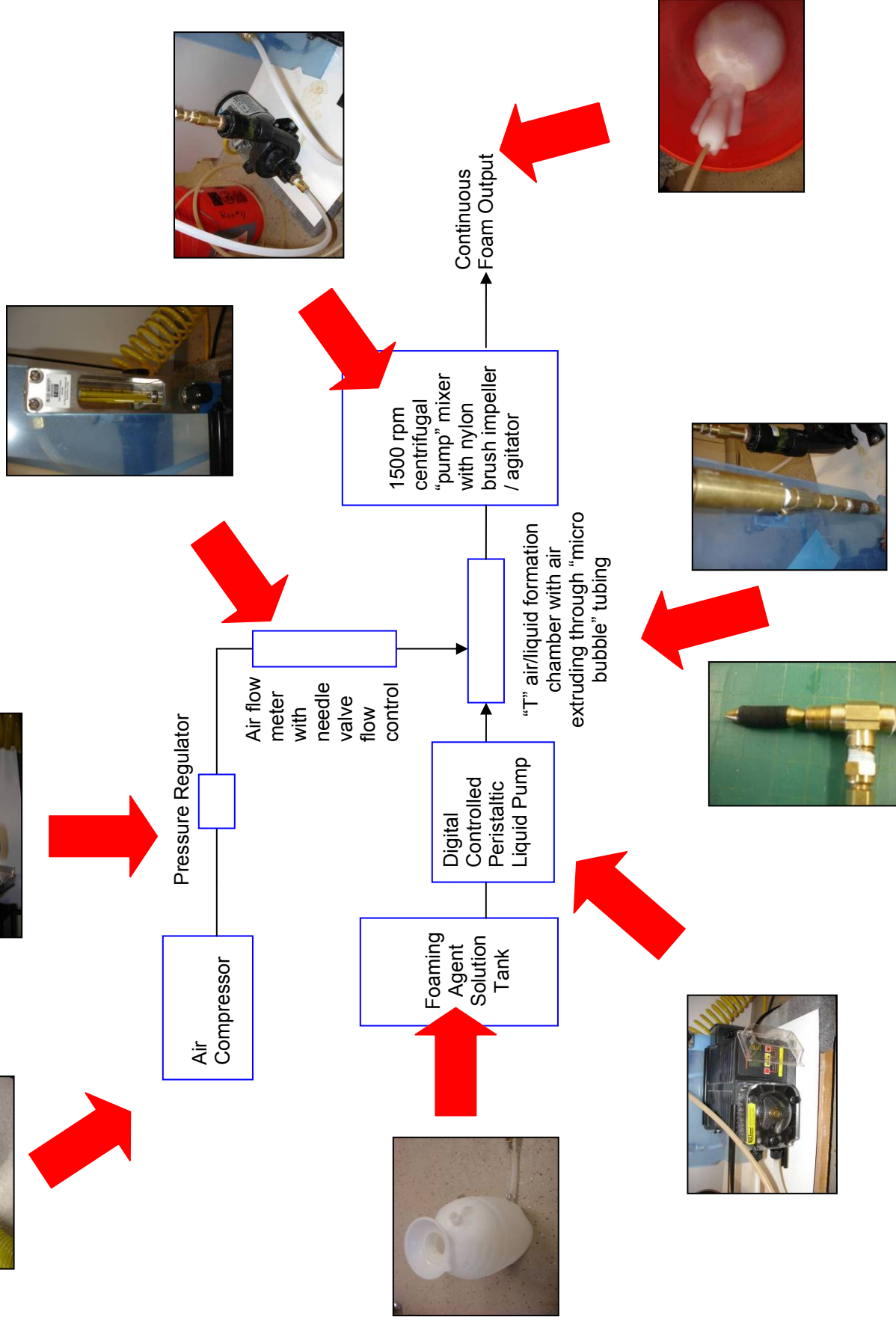4
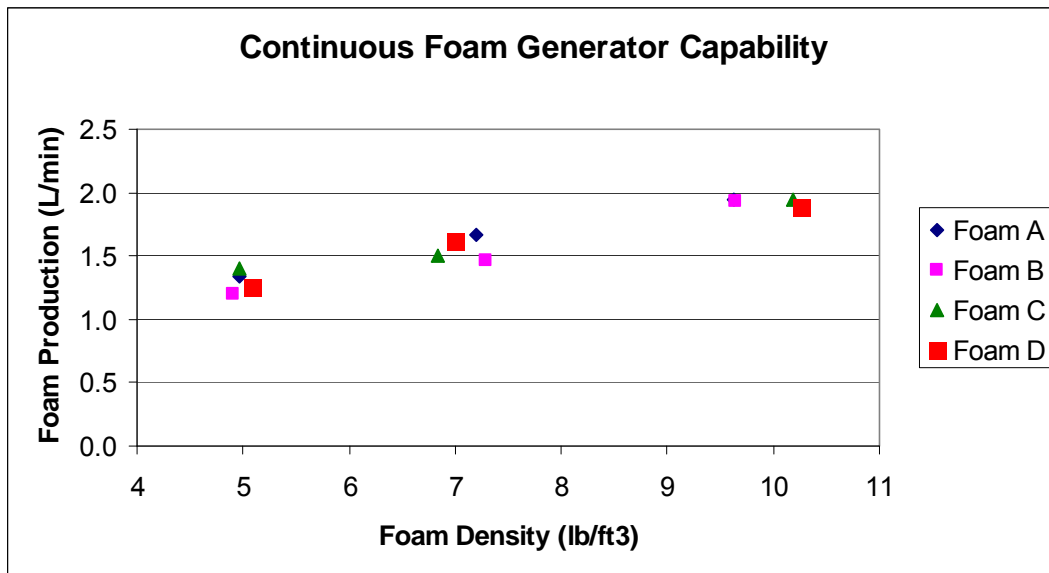
Figure 2: Continuous Foam Generator Layout

Air Compressor

Pressure Regulator

Air flow meter with needle valve flow control

1500 rpm centrifugal "pump" mixer with nylon brush impeller / agitator

Continuous Foam Output

"T" air/liquid formation chamber with air extruding through "micro bubble" tubing

Digital Controlled Peristaltic Liquid Pump

Foaming Agent Solution Tank

Figure 3 – Continuous Foam Generator

Figure 4 – Continuous Foam Generator Capability

Three foam densities were targeted as per patent documentation for the gypsum industry; 5, 7 and 10 lb/ft^3. Foaming agent solution concentrations used were 0.169%, 0.152% and 0.115% actives for each foam density respectively. "% actives" is the convention used to describe the percent by volume of surfactant molecule in the final solution used in the foam generator. These dilute solutions were produced by further diluting industry representative commercial samples that as delivered are typically 40% solutions. Foam generator settings were chosen such that the air output from the compressor was constant, set at approximately 1.0 l/min at a pressure of 40 psi. Although

air flow was controllable in the system using the needle valve of the flow meter, this setting proved difficult to vary with a high degree of precision. Ultimately, the foam density was altered using the digitally controlled peristaltic pump which precisely varied the volume of foaming agent solution added. A consequence of this setup was that increasing foam density also increased the amount of foam produced over time which was necessary to consider when specific foam volume additions were required.

Cubes were produced by the following method:
- Combining plaster with a determined amount of gauging water, allowing the plaster to wet for 30 seconds and mixing for 5 seconds in a high shear kitchen blender.
- Combining this slurry mixture with a specific foam volume produced by the continuous foam generator, mixing for 20 seconds in a low shear tilt-head stand mixer with a wire whip mixer attachment.
- Pouring the cubes into a 2" brass cube mold and allowing the mixture to set (~ 30 minutes).
- Removing the cubes from the mold and drying them overnight at 45°C.

Each cube mix consisted of 600g of United States Gypsum No1 Moulding Plaster with 430 ml of total water, split as necessary between gauging water and foam water. This resulted in an overall mix water demand of 71.6 ml/100g of plaster. Cubes mixes were iteratively produced, maintaining the constant total water while varying the amount of foam volume added until a target density of 0.577 g/ml was met, which calculates to an equivalent 1/2" board weight of 1500 lb/msf. Note that this method of iterative weight normalization was performed at the cube level evaluation as opposed to the board level evaluation as was described in the original proposal. The purpose of this change was to identify which slurry mixes behave differently as cubes as compared to boards effectively identifying if some foam bubble structures are more or less robust to being formed in a sheet as compared to a cube. Overall, 46 mixes were attempted in order to achieve the necessary 12 in the target range. Table 1 describes the cube details for each target mix produced with the continuous foam generation system. Foaming agent concentration in each overall mix did vary to some degree as the amount of foam required to reach a specific target density varied slightly. In general, this concentration was 0.012 – 0.022% actives by weight of plaster. This range identifies the degree of efficiency that the foaming agents are able to produce bubbles, although it is not yet known if being able to produce bubbles with less foaming agent necessarily produces the most ideal bubble structures.

Table 1 – Cube Production with the continuous system

Foaming Agent	foam density (lb/ft^3)	foam production (l/min)	Weight % foam actives in foaming agent solution	Average cube density (g/ml)	Average Equivalent 1/2" board weight (lb/msf)	Weight % foam actives in overall mix (on plaster)
Foam A	4.96	1.33	0.169	0.572	1487	0.013
	7.20	1.67	0.152	0.572	1488	0.016
	9.63	1.94	0.115	0.587	1526	0.017
Foam B	4.90	1.20	0.169	0.586	1525	0.012
	7.30	1.46	0.152	0.596	1551	0.013
	9.65	1.94	0.115	0.569	1480	0.014
Foam C	4.97	1.40	0.169	0.567	1475	0.013
	6.84	1.50	0.152	0.579	1507	0.013
	10.19	1.94	0.115	0.566	1473	0.014
Foam D	5.09	1.25	0.169	0.588	1530	0.017
	7.00	1.62	0.152	0.575	1495	0.022
	10.26	1.88	0.115	0.594	1545	0.019
Average				0.579	1507	0.015
σ				0.011	28	0.003

Cubes were similarly produced using a non-continuous foam generation system in order to compare the effects of the continuous system versus the previous standard. A Hamilton Beach Drink Mixer was utilized to generate foam, using the same foaming agent concentration and amount of solution as determined from the continuous trials. Table 2 describes the details of the non-continuous mixes, wherein foam density is reported as "foam density equivalent", indicating that the specific foam density for each non-continuous batch was not measured but is meant to be directly compared with the equivalent input continuously produced counterpart. As foam production was performed batch-wise, no rate of production is given.

Table 2 – Cube Production with the non-continuous system

Foaming Agent	foam density equivalent (lb/ft^3)	Weight % foam actives in foaming agent solution	Average cube density (g/ml)	Average Equivalent 1/2" board weight (lb/msf)	Weight % foam actives in overall mix (on plaster)
Foam A	4.96	0.169	0.734	1908	0.013
	7.20	0.152	0.727	1890	0.016
	9.63	0.115	0.634	1648	0.017
Foam B	4.90	0.169	0.763	1983	0.012
	7.30	0.152	0.735	1913	0.013
	9.65	0.115	0.688	1789	0.014
Foam C	4.97	0.169	0.681	1771	0.013
	6.84	0.152	0.710	1847	0.013
	10.19	0.115	0.647	1682	0.014
Foam D	5.09	0.169	0.748	1944	0.017
	7.00	0.152	0.763	1985	0.022
	10.26	0.115	0.620	1614	0.019
Average			0.704	1831	0.015
σ			0.050	130	0.003

4. Compressive Strength Testing

Compressive strength testing of the 2" cubes (72) and comparison versus the "normal" curve. Published data exists for strength versus gypsum material density while varying slurry water. This shall be considered the base case to be compared, with similar densities being investigated but created from foam additions rather than created from undesirable extra water addition.

USG has previously published strength results for compressive strengths measured for various plaster/water ratio compositions. Recalculating these ratios to indicate equivalent board weight gives the following relationship as identified in Figure 5.
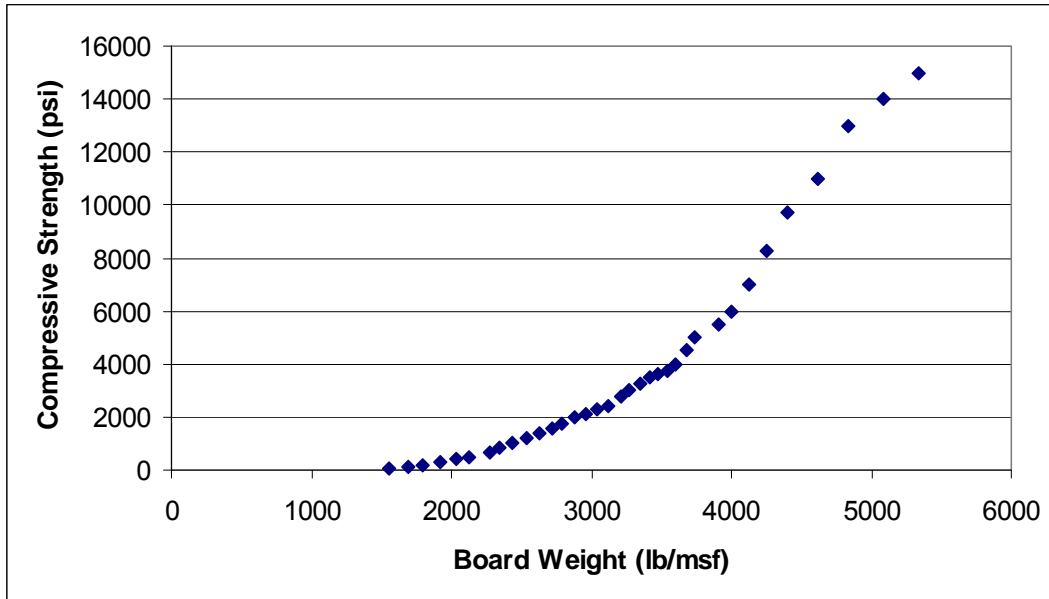
Figure 5 – Industry Published Gypsum Compressive Strength versus Equivalent Board Weight

Unfortunately, a direct comparison between these plaster/water composites and typical manufactured board weights is not entirely reasonable as the weights quickly begin to surpass what is likely reasonable for a board installer to work with. Cubes were crushed using a hydraulic press test machine that measures the peak force of calibrated pressure transducer. The 1500 lb/msf continuous foam cube samples measured reasonable strengths for their weight, some mixes marginally better than others but with no obvious deviation from normal. Results are shown in Figure 6.
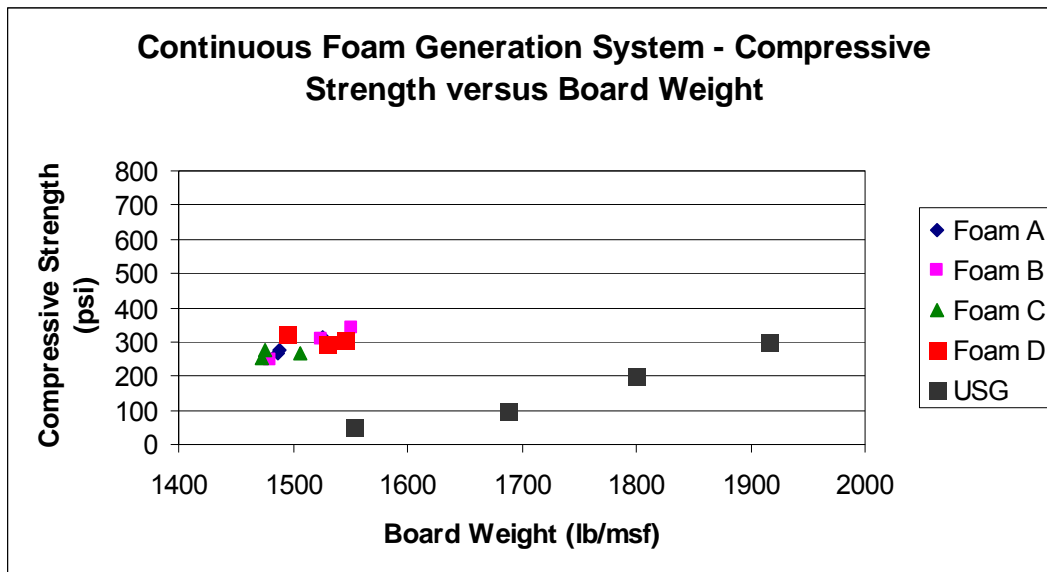
Figure 6 –Compressive Strength versus Cube Equivalent Board Weight Data

Batch samples were also measured and showed relatively large variation in the strengths and weights observed when considering that from a formulation standpoint they had the same mix proportions as the continuous mixes (see Figure 7). This likely identifies the importance of foam production processing. In general it was found that the batch foam generator produced results more similar to the continuous system at higher foam weights (10 lb/ft^3). At lower foam weight equivalent solutions, the batch generator does not entrain enough air into the foam which is necessary to produce light weight boards.
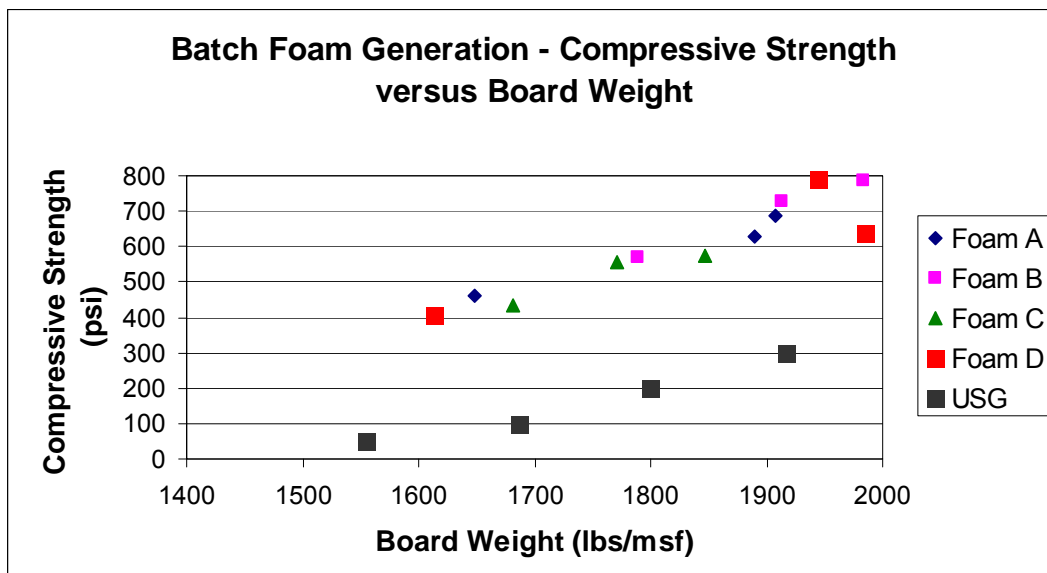
Figure 7 –Compressive Strength versus Cube Equivalent Board Weight Data
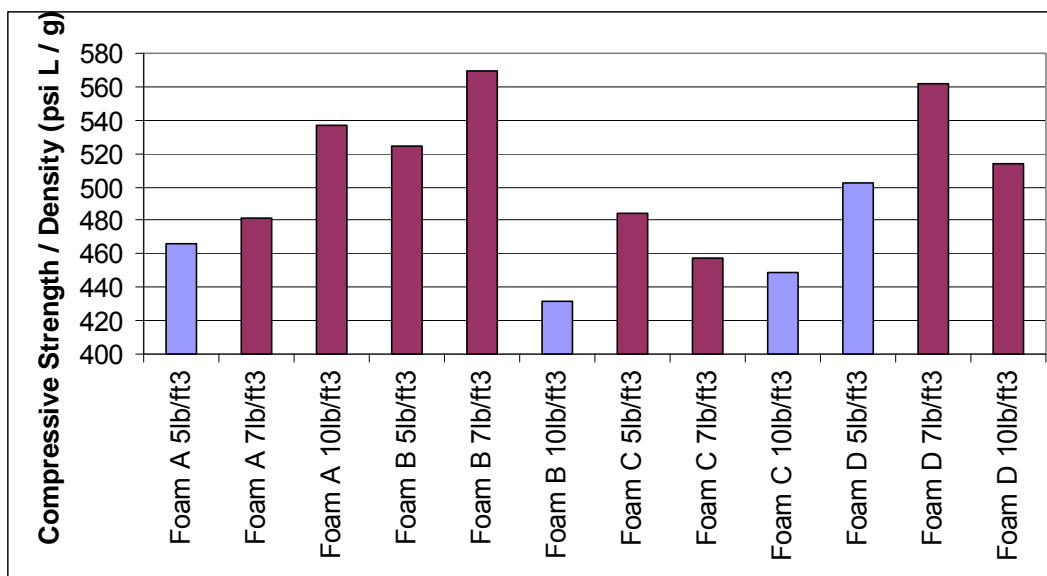
Figure 8 – Compressive Strength / Density Data plotted by Foaming Agent and Foam Weight

Comparing the efficiency of strength per density factors for all foam formulations identified two candidates from each foaming agent for continued study in Section III. These candidates are indicated in maroon.

5. Laboratory Board Samples

Laboratory board samples were created using continuously generated foams at usage rates that resulted in a constant density of ~ 0.6g/ml or 1500 lbs/msf but had different core structure configurations. (*Note: pounds per thousand square feet of board surface area is the industry standard measure for board weight*) In using 4 different chemical foams at 2 different formulation levels as chosen from the foam system qualification study (8 different board samples; 3 boards for each sample required for full testing) it is anticipated that at least 4 different resulting structures will be generated. These 4 chosen most different structures will be determined through low resolution CT (see Section 6) and will be the final highlighted results of this research study. It is important to note that the main purpose of this experiment is not to correlate foaming agent brand with structures generated. The intent is to use different foaming agents to generate an array of different structures to chose from and correlate 4 of those unique structures with performance. It is expected that some structures may be produced using alternate means but is not intended to be evaluated. It is also expected that some structures produced may be similar despite different starting foam inputs, hence the generation of 8 samples, intending detailed evaluation of 4. Industry modeled generic formulations will otherwise be used for board ingredients (plaster, set accelerators, starch etc.) Given that industry applicable formulations will be used along with industry representative lab processing methods, it is expected that the array of samples generated will be representative of the range of structures in commercial board samples within reasonable minor variation. Each sample requires approximately 1/4 day of dedicated processing from formation to drying. Formulation trials will require tuning the necessary foam input quantities to achieve constant density. Images of the continuous foam generation system and final lab board samples will be presented.

Boards were formed using a similar method to that used to produce cubes with the following exceptions:

- 3g of starch and 1g of ball milled gypsum accelerator was added to the 600g hemihydrate powder premix; starch is necessary to help bind the core and the interface of paper lined

boards and gypsum accelerator is used to increase the rate of the hemihydrate to gypsum setting reaction more similar to the setting rate of board plants.

- Samples produced were paper lined, face and back with identical liners obtained from the "end" of a roll of a local board producer liner supply
- Samples were dried face up in 3 stages: 246°C, 107°C and 45°C; the purpose of stage drying is to allow maximum rates of drying without recalcining the faces of the board with high surface temperatures before the middle of the core is dried, again more similar to the processes that exist in board plants.

Samples produced were 1/2" thick, 7" wide and trimmed to 11" long. Sample lengths varied slightly corresponding with the mix volume produced.

Figure 9 – 3 Cubes and a Board Sample (shown with an 8.5" X 11" piece of paper and a 15" ruler as reference)

	foam weight (lb/ft3)	foam production (L/min)	Board Weight (lbs/msf)
Foam A	7.20	1.67	1752
Foam A	9.63	1.94	1662
Foam B	4.90	1.20	1631
Foam B	7.30	1.46	1564
Foam C	4.97	1.40	1694
Foam C	6.84	1.50	1541
Foam D	7.00	1.62	1607
Foam D	10.26	1.88	1731
Average			1649
σ			76

Table 3 – Board Sample Production with the continuous system

Overall, the boards produced averaged 134 pounds heavier than the cubes made with equivalent mixes. As described, due to the extrusion process of board formation, a larger area of slurry surface is contacted for a given volume when compared to cube formation. It is reasonable to expect that foam void content is likely negatively affected by this process, resulting in boards that have increased weight.
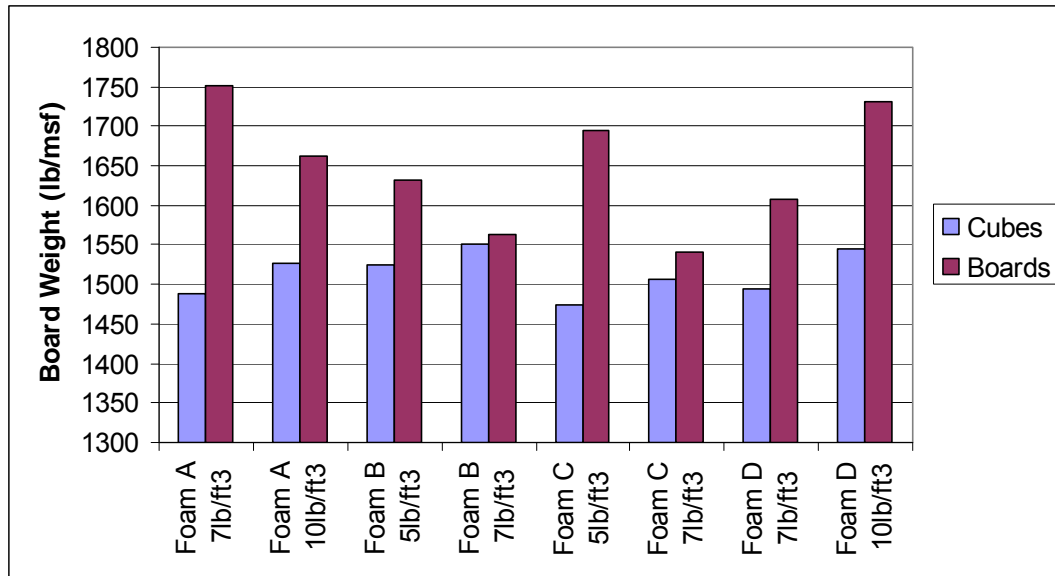

Figure 10 – Board Weights Produced for Equivalent Cube and Board Mixes

Amongst those evaluated Foam B tended to have the smallest differential between cube and board, indicating it is likely the most stable, independent of formation geometry.

6. Computed Tomography (CT) Scanning

CT scan of laboratory boards including bubble size distribution calculation, z-density profiling, visual representations and a comparison to a commercial sample. The 8 boards will be scanned in 2 scans at low resolution (4 per scan), after which 4 unique structure candidates for higher resolution scans will be chosen (an additional 4 scans). A bubble size distribution is a histogram graph outlining % of total bubble volume versus binned bubble diameter. Z-density is an XY line plot of sample density as a function of depth through the thickness of the board. Visual representations will be displayed as .jpeg images, 3D rendered surface representations and QuickTime .mov movies showing an animated effect of traveling through the board core.

Initial post-production analysis of the 8 lab boards consisted of surface variability checks, wherein depressions in the paper-surface were noted through degree of deflection from straight-edge. In addition, the tensile properties of the paper were tested via pressure-deformation to determine if delamination or undesirable settling/aggregation of the bubble structure occurred in proximity to the paper. A standard area of the board sample, assuming no surface or paper tensile faults, was sampled along the board center-line, 5 cm from the board end. Samples were cut as 10 cm diameter half circles. 4 samples were present in each low res scan, each pair stacked on another, mounted in a plastic sample chamber (see Figure 11). Since the boards were lab produced, there likely is no machine direction bias present in the core. However, the influence of gravity is present with the gravitational 'up' being noted and retained throughout all scans and imagery presented (+Z).
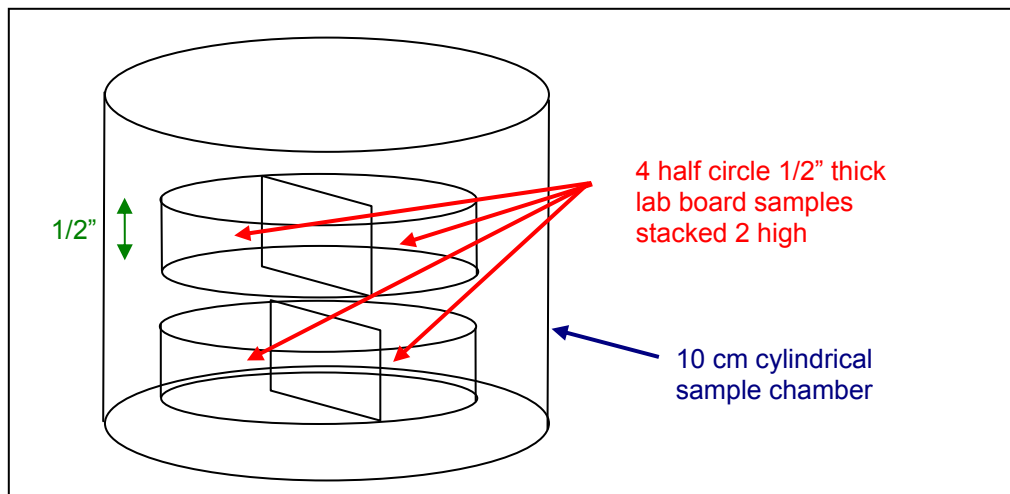
Figure 11 – CT Scan Sample Orientation

Samples are presented in 3D CT imagery as a 2D image for each orthogonal plane. Water and air standards were a component of all scanning wherein these standards were used to calibrate the density values observed in samples of unknown density. The images themselves are 16-bit grayscale, representing a potential 65,000 degrees of density for each voxel. Lighter areas indicate high density while darker areas indicate low density (see Figures 12 and 13).
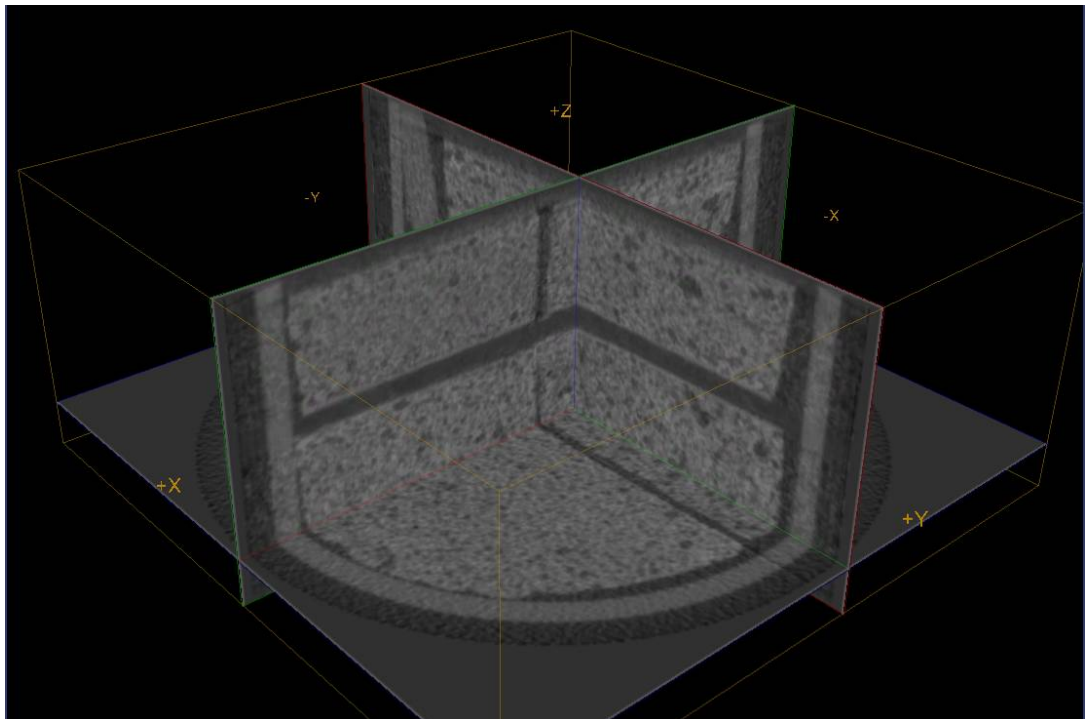

Figure 12 – 1ˢᵗ Low Resolution CT scan representation of 4 samples in the sample chamber
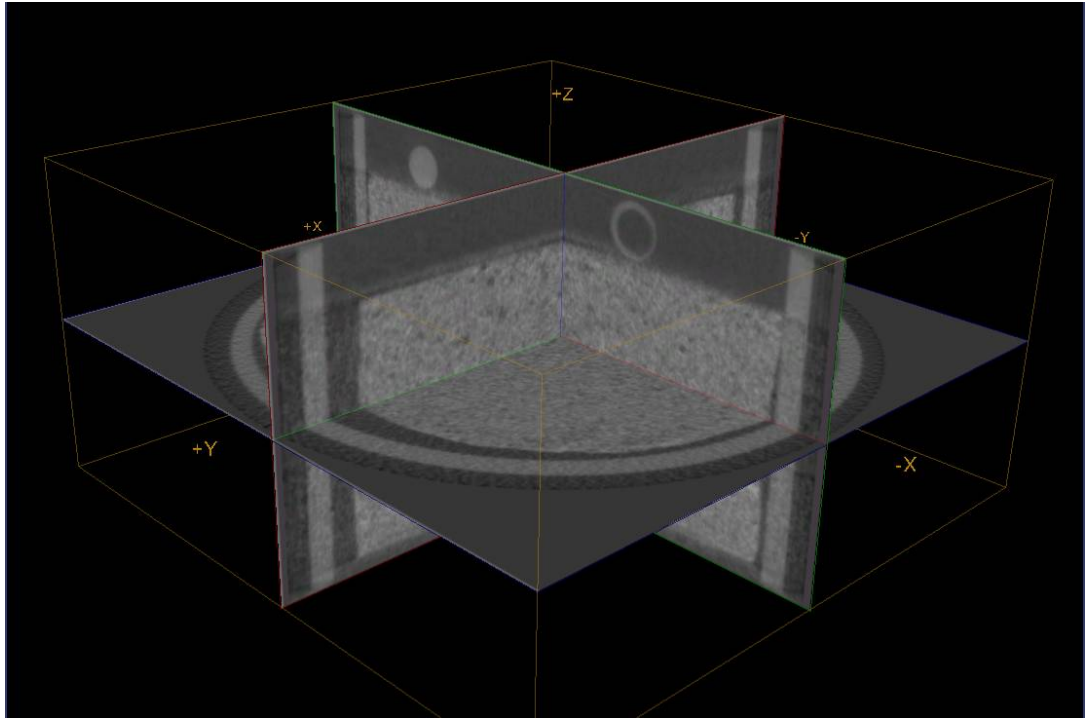
Figure 13 – 2nd Low Resolution CT scan representation of 4 samples in the sample chamber

Four samples were chosen from the 8 cores observed in the low resolution scans. The selection criteria for this selection for high resolution scanning included the following characteristics:

- relatively homogeneous core density
- consistent bubbles throughout the core
- no undue gravimetric setting artifacts (i.e. increasing density with gravity direction)
- complete lamination of paper to gypsum board core.

The samples selected for high resolution scanning are not necessarily known to be 'ideal' boards. Rather the 4 samples were ranked with regard to the above criteria amongst the 8 boards produced. Furthermore, the selection was not a guarantee that the resampling of the board for high resolution scanning would be free of production artifacts (i.e. qualities that contravene the above criteria).

To this effect, the Foam A 10lb/ft^3, Foam B 7lb/ft^3, Foam C 7lb/ft^3 and Foam D 10 lb/ft^3 boards were scanned at high resolution (16.6 µm^3 per voxel) to attain detailed 3D imagery of the complete gypsum board profiles. This level of detail allows for accurate air-bubble analysis (see Figures 14 to 18 for image representations of the CT results). Scanned volumes were approximately 1.9 cm X 1.9 cm X 1.3 cm (1/2" in thickness) in size. *Note that the commercial sample comparisons presented here are the results of previous work (2005) and were not remeasured for CT scan within the scope of this project.*
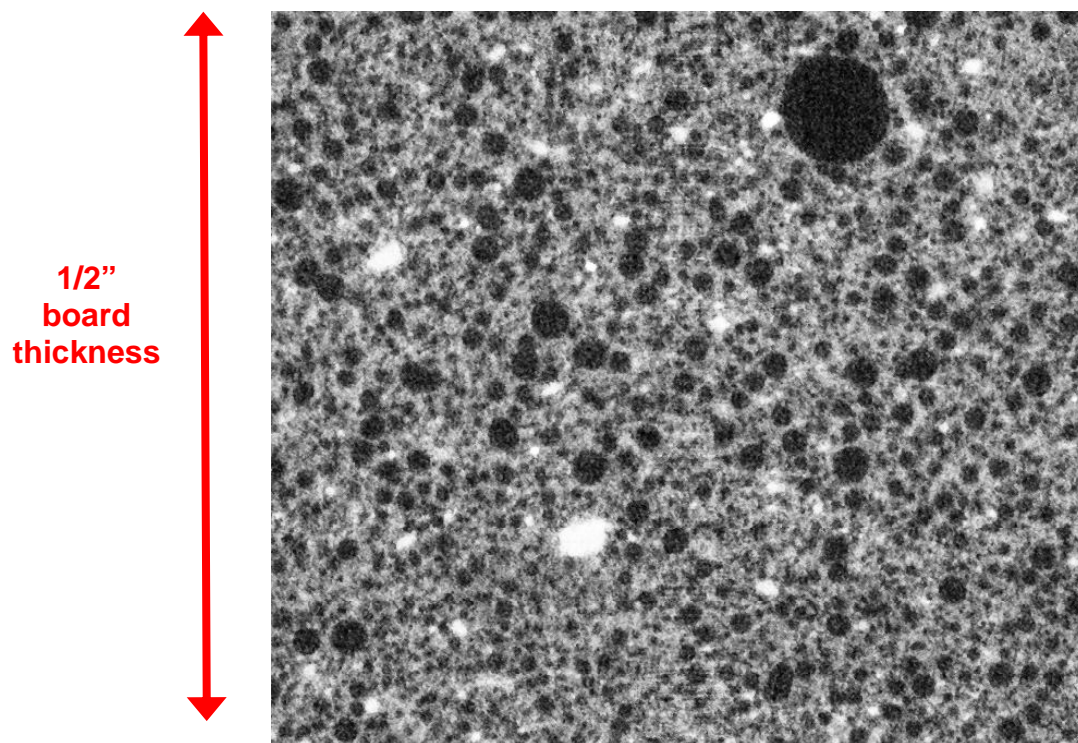
1/2" board thickness

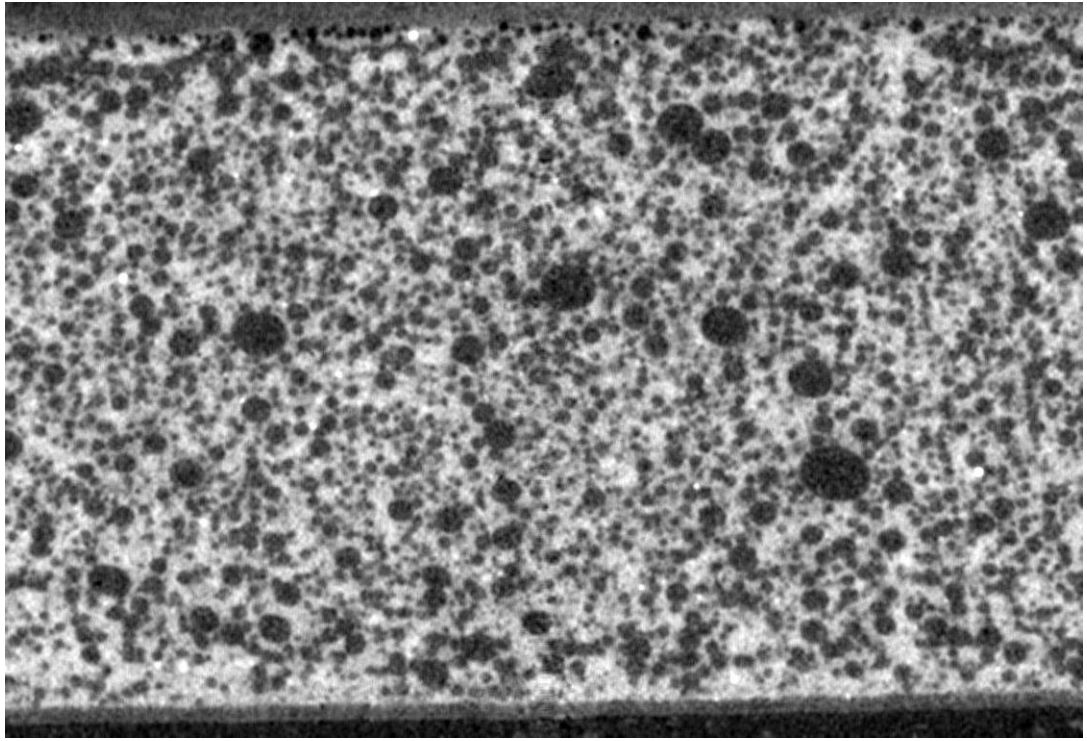*Figure 14 – CT scan z-profile of Commercial Board A*

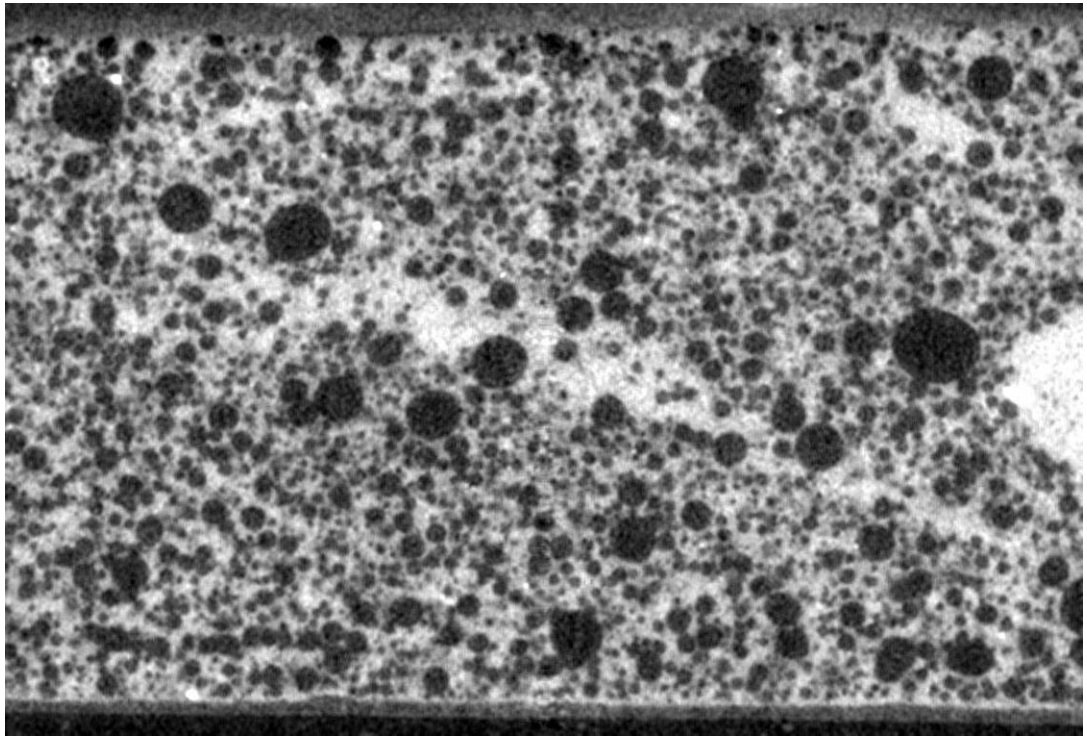*Figure 15 – CT scan z-profile of a Foam A 10lb/ft^3 board*

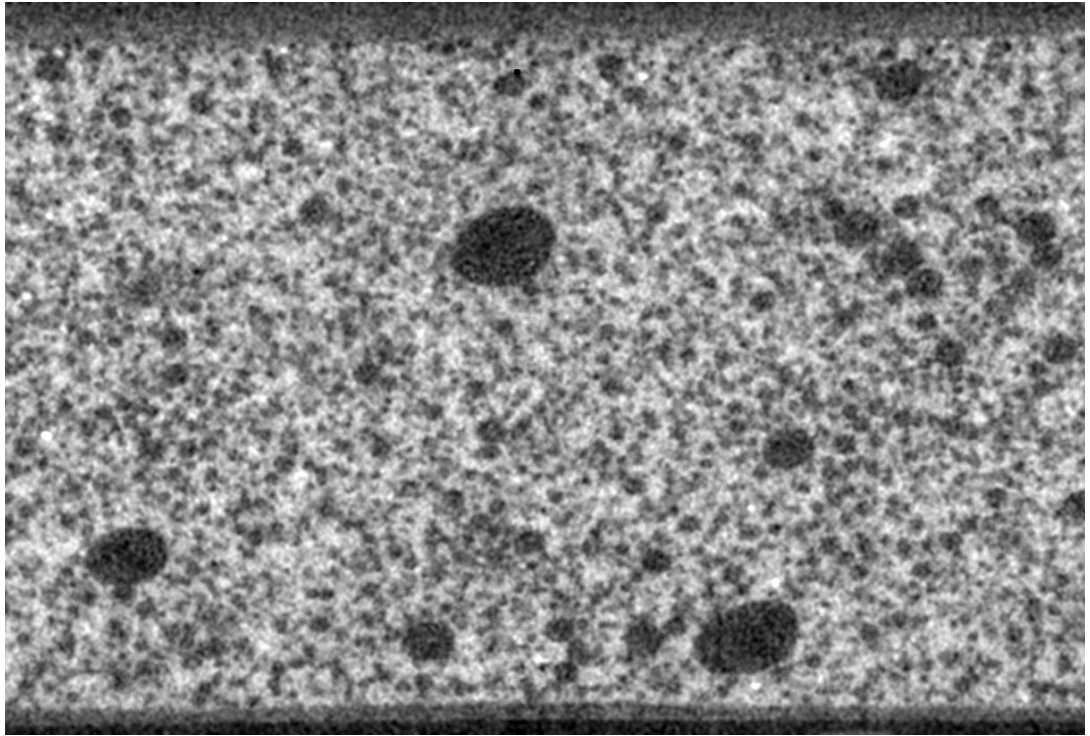*Figure 16 – CT scan z-profile of a Foam B 7lb/ft^3 board*

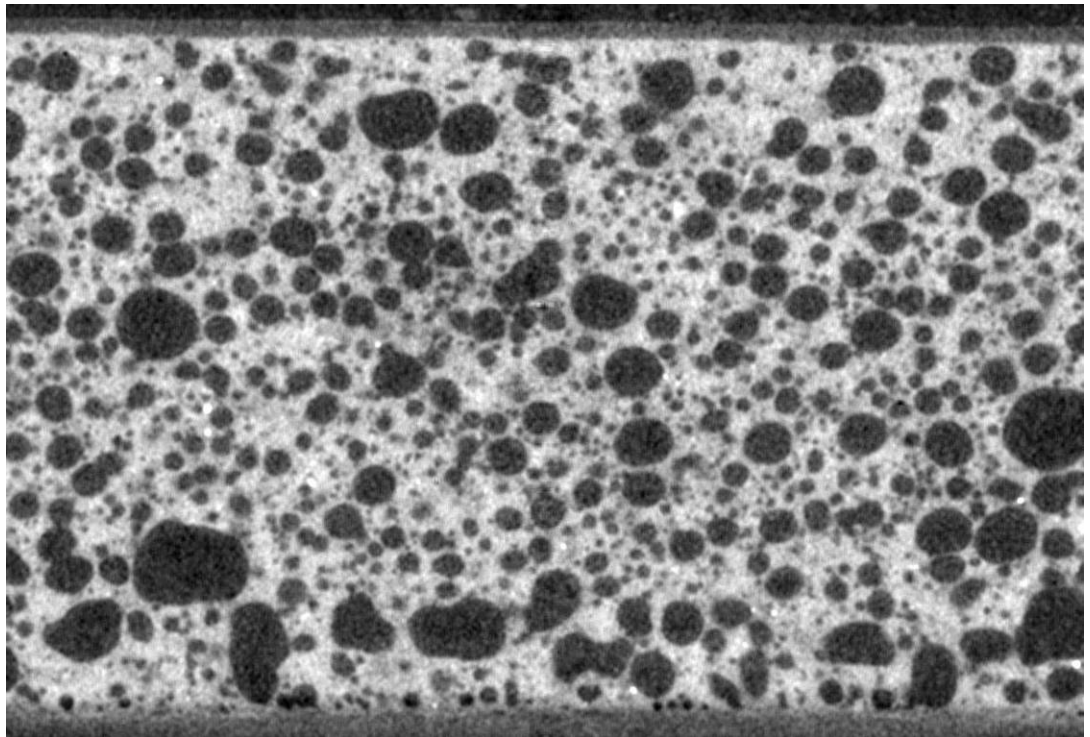*Figure 17 – CT scan z-profile of a Foam C 7lb/ft^3 board*

Figure 18 – CT scan z-profile of a Foam D 10lb/ft^3 board

Calculations were performed on the CT scan data of the lab boards previously described. Board weights of the lab board generated samples used for the high resolution scans are included in Figure 19.
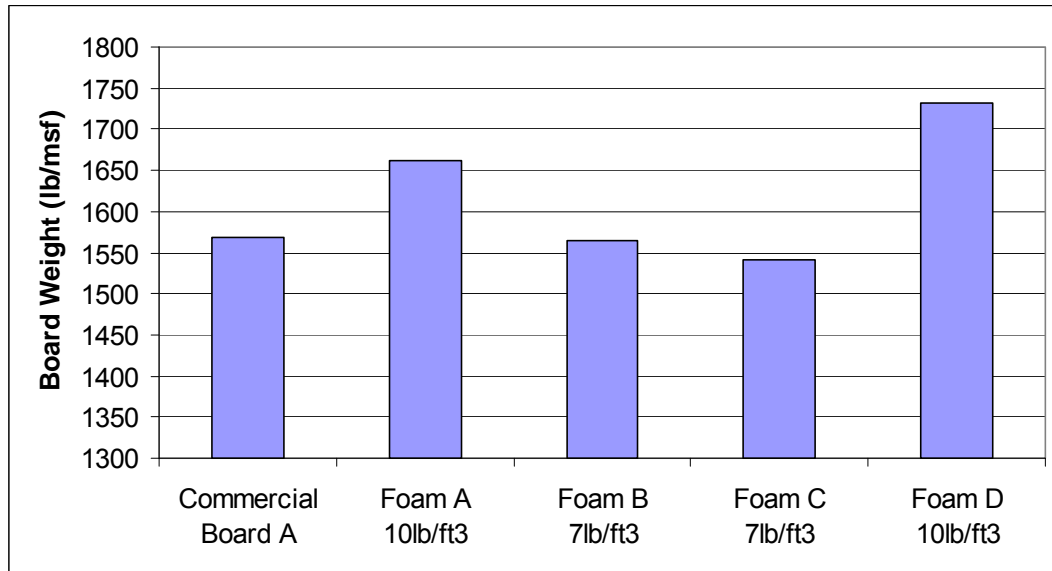
Figure 19 – Board weights of high resolution CT scanned samples

In general, the weights of the board samples created were relatively consistent considering that no mix modifications were made to produce boards instead of cubes. After scanned results were available, image analysis procedures were applied in order to isolate the volume of low density bubble voids within the structure such that they may be counted and evaluated for size. Innogyps uses a proprietary algorithm coded in Microsoft Visual Basic (Excel Macro) to perform these bubble size calculations. For the samples measured in this experiment, Figure 20 shows the relative overall bubble count in each defined region of interest volume.
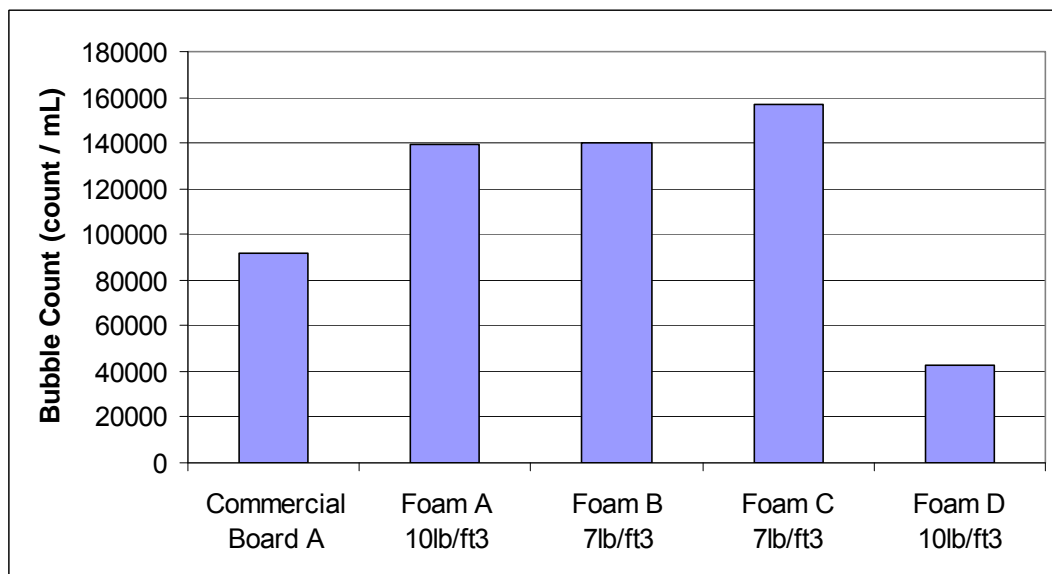

Figure 20 – Bubble counts per ml of volume of CT scanned boards

Clearly Foam D 10lb/ft^3 showed a largely reduced bubble count from the other 3 foaming agent

samples evaluated in the high resolution investigation. This result generally agrees with what was observed subjectively in the included images which show Foam D 10lb/ft^3 having a much larger bubble void structure.

The size distribution of these counted bubbles is included in Figure 21. Note that this plot is presented in a continuous linear form although the actual data generated is a binned histogram format. In general, this data can be considered similar to a particle size distribution which describes how much volume a given binned range of particle size represents when compared to the total volume. For this calculation each bin was 20 μm wide and the total bubble volume was taken directly from the summed volume of all individual bubbles.
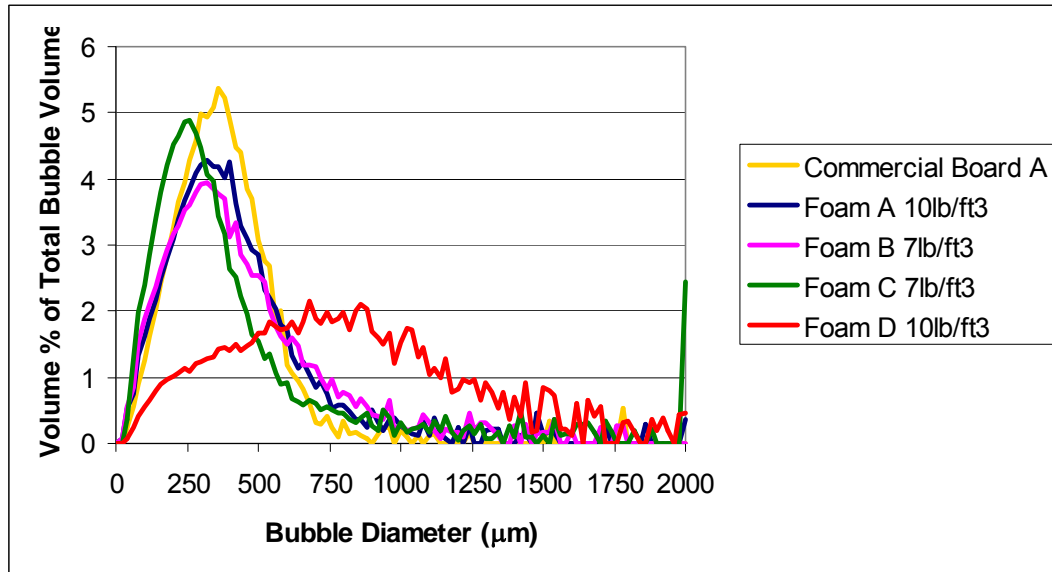

Figure 21 – Bubble size distribution of CT scanned boards

Note that the median bubble size of Foam A, B and C is likely 250-300 μm where as Foam D is likely 750 μm. The commercial sample had a bubble size distribution similar to Foam A, B and C.

Finally, a plot of Hounsfield Unit versus board thickness is presented in Figure 22. Hounsfield Units are a CT-specific quantitative scale describing radiodensity. This specific plot is typically referred to as a z-density profile, describing the relationship between the average density of the board core at any given plane through the entire thickness. Thickness results are presented with 0 mm being the board face and ~ 12.5 mm being the board backside. Note that a value of 0 HU corresponds to a calibrated value for the observed atomic density of water. Although macroscopic density (like board weight) can be correlated with atomic density, it is not exactly a linear relationship therefore results are presented in HU.

Figure 22 – HU versus thickness
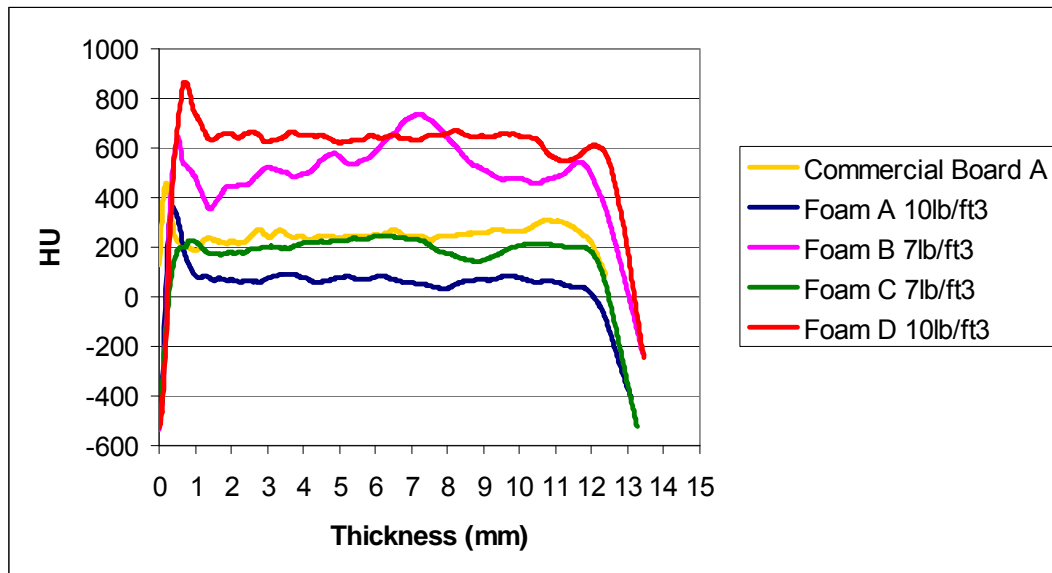
This plot clearly identifies Foam D as being the heaviest board sample with a relatively flat profile from front to back. Foam B is identified here as likely being the poorest uniform sample as the structure is shown to have an unusual peak at approximately the 7 mm depth. Reviewing the actual images further, it can be observed that this behavior is likely due to improper mixing with that sample as clearly some higher density white banding is present through the core. It is believed that this behavior is not likely due to the particular foaming agent but instead is a source of experimental error in sample preparation.

Under normal circumstances, it is expected that the average intensity of the z-density profile for a given board should track with the macroscopic board weight but it is observed here that the 3 lightest samples track in the opposite order. Although the banding in Foam B may explain that odd behavior, no apparent reason would seem to make sense for the order of A and C. Some possible explanations may include macroscopic board weights not being representative of the actual sample segment which is measured or perhaps unideal applied air/water HU calibration factors in subsequent scans. Future scans are proposed to be measured with more in-scan gypsum density standards with which to perform a multi-point calibration to account for this possibility.

7. Fire Resistance Testing

Furnace fire resistance testing of laboratory boards measuring overall shrinkage after firing and after surface cracking was performed. Surface cracks were calculated from digital image analysis. By thresholding binary images at a particular intensity, counts were determined for percent of total area for crack formations. Cracks show up darker than the board surface in photographs. One sample was be required for each test (8 total).

Lab board samples were again duplicated and fired in a commercial electric kiln. Two boards were fired in each run and were allowed to cool overnight before being removed from the kiln for measurement. The samples were not held or restrained in any way. Figure 23 shows 2 boards in the bottom of the kiln being fired.
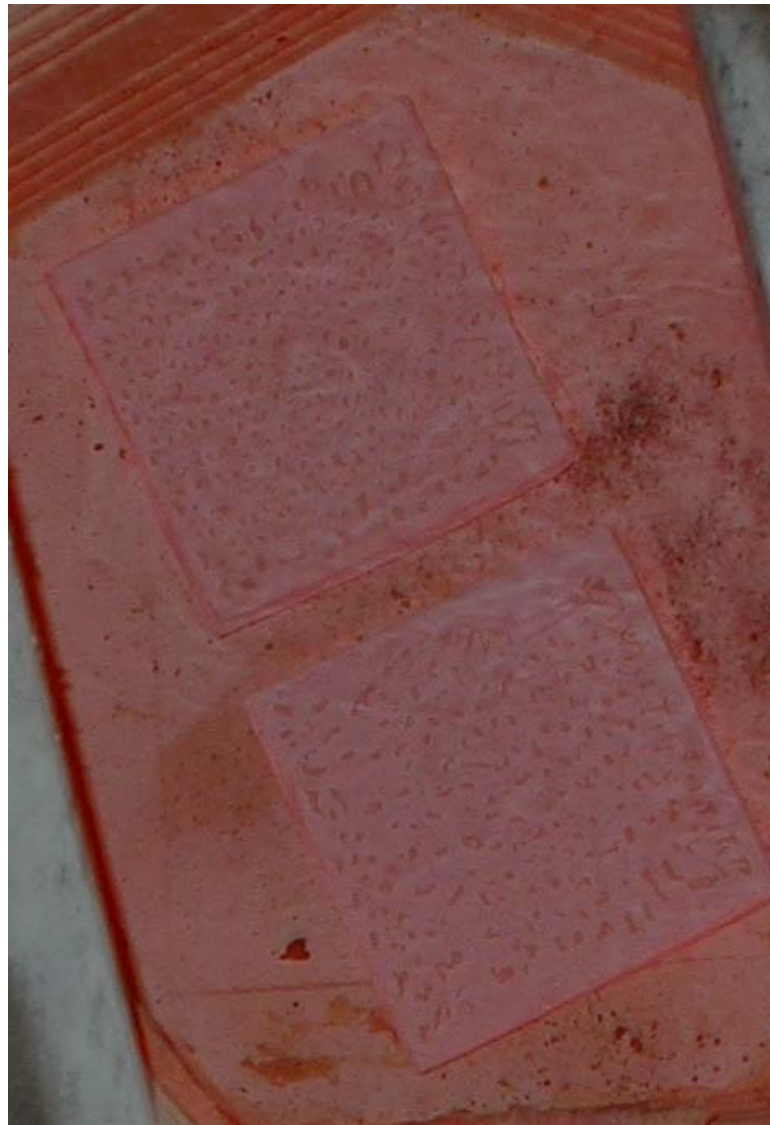
Figure 23 –Board samples being fired in an electric kiln

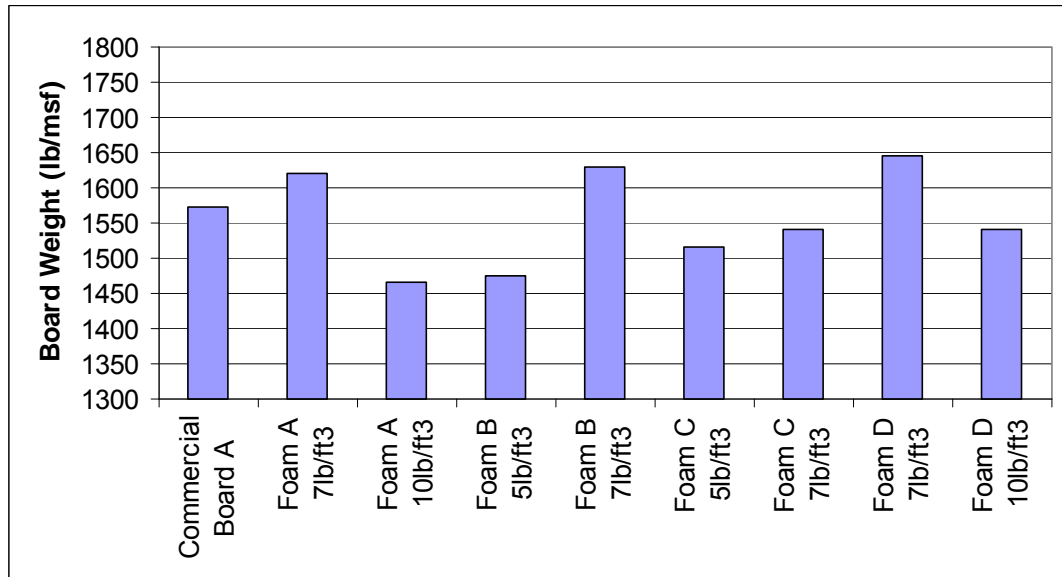Board weights of the samples produced are given in Figure 24.

Figure 24 – Board weights of fired lab board samples

Again, reasonable board weights were produced for these samples, although some previously identified trends of higher stability foams are less evident here, perhaps outlining a larger variation in reproducible board sample weights as compared to cubes. Previous experience has shown that lab board weights can be somewhat variable depending on the producing operator. Nonetheless, if major differences in fire resistance performance are observed, it may be necessary to consider the contribution of board weight.

Thermocouple measurements of the chamber temperature inside the electric kiln during firing were recorded for each firing batch. These results are included as Figure 25.
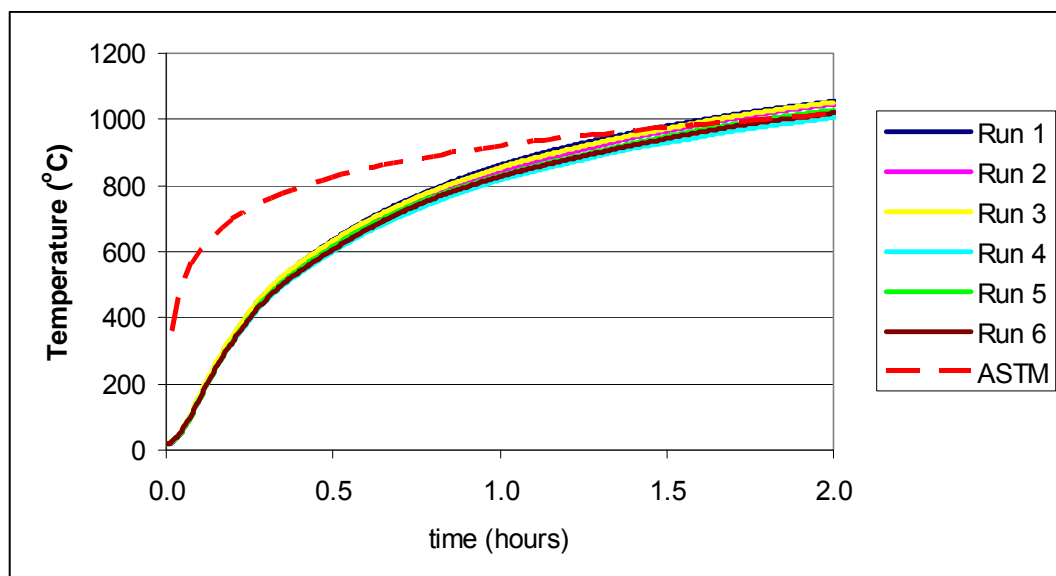

Figure 25 – Temperature traces of fired lab boards

Time-temperature ramp repeatability was generally good, all samples starting from room temperature and reaching approximately 1000 degC in 2 hours. The ramp was less severe than that specified by ASTM in the first hour but the maximum temperature reached at 2 hours was similar enough for a reasonable comparison. A more sophisticated gas furnace with venting capability is normally used in full scale fire testing but for small scale lab measurements an electric kiln is a much safer alternative.

Thickness measurements of the approximately 1/2" samples were taken at 8 positions along the edge of the fired samples and averaged. The fired samples were approximately 6" square and 0.0001" outside calipers were used for this measurement. These samples were remeasured in the same approximate locations after firing and a fraction (percent) was calculated from the original thickness. Note that the measurement locations after firing are described as approximately the same because the samples do shrink making finding the same position somewhat difficult.
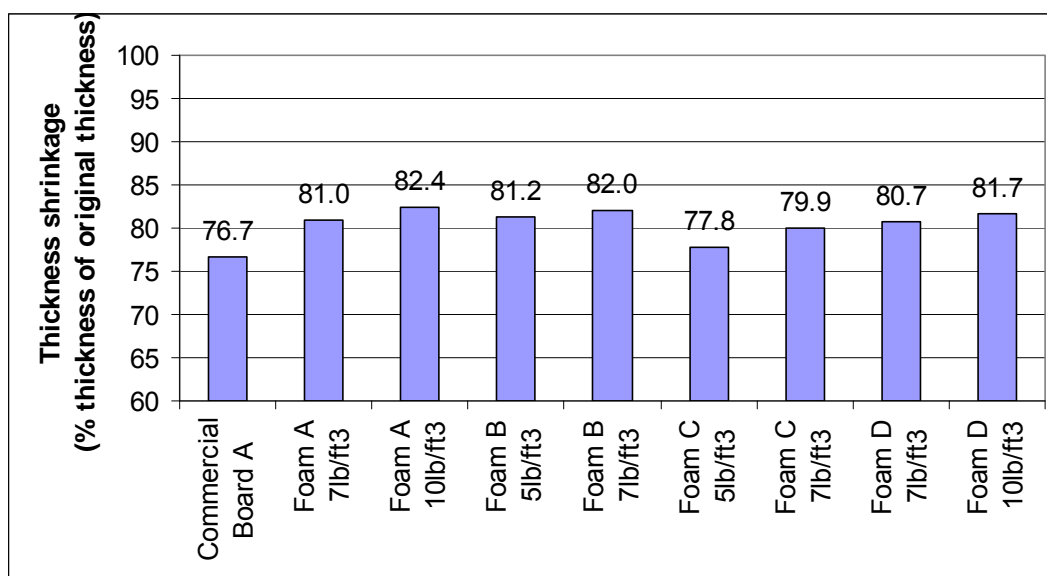

Figure 26 – Thickness shrinkage of fired samples

Thickness shrinkage showed slightly higher numbers (less shrinkage) than that observed with commercial samples, possibly due to different gypsum core purity and different temperature response of any associated impurities. Different paper thickness may have also contributed to this difference as this thickness is mostly lost in firing to these temperatures. All lab samples seemed to perform similarly as likely some error could be expected in this measurement due to the measurement position variation described earlier.

Machine and cross direction sample length measurements were again recorded before and after firing and are presented in Figures 27 and 28 as shrinkage results. These measurements were performed using a tape measure indexed to 1/32". In practice, due to the sample orientation during firing, some convex curvature of the samples was observed to occur. This behavior was a direct result of placing the samples face up on the fire bricks in the base of the kiln, meaning that samples were more likely to contract on their face up side during cooling. To compensate for this curvature, length measurements were performed on string line references which were used to determine the actual length of the samples including curvature.
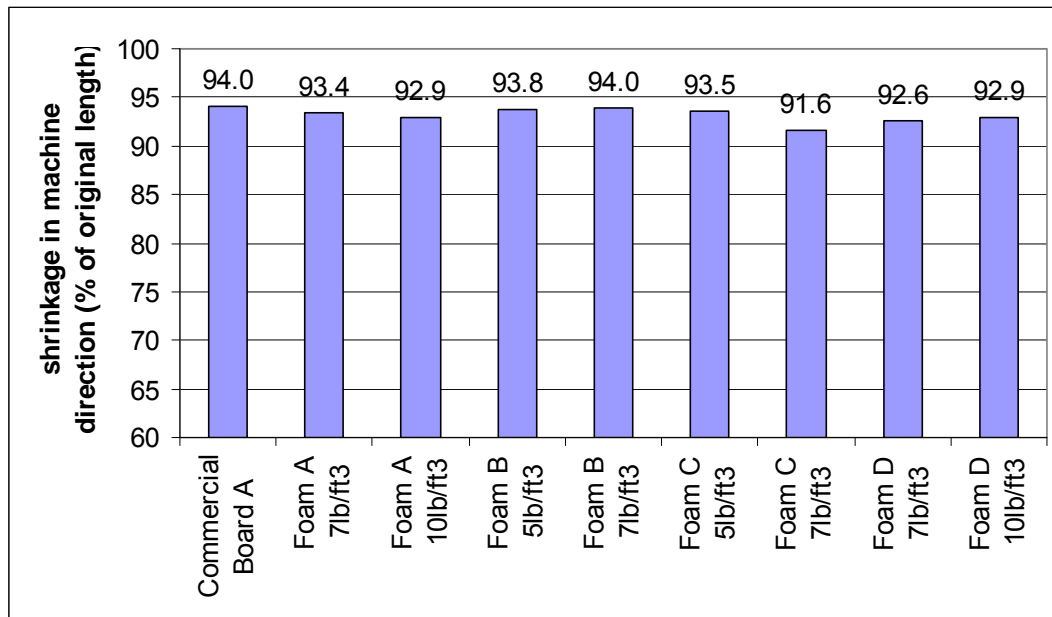
Figure 27 – Shrinkage in machine direction of fired samples

Again, fairly consistent results were observed across all samples further indicating little observed fire resistance dependence on foam structure.
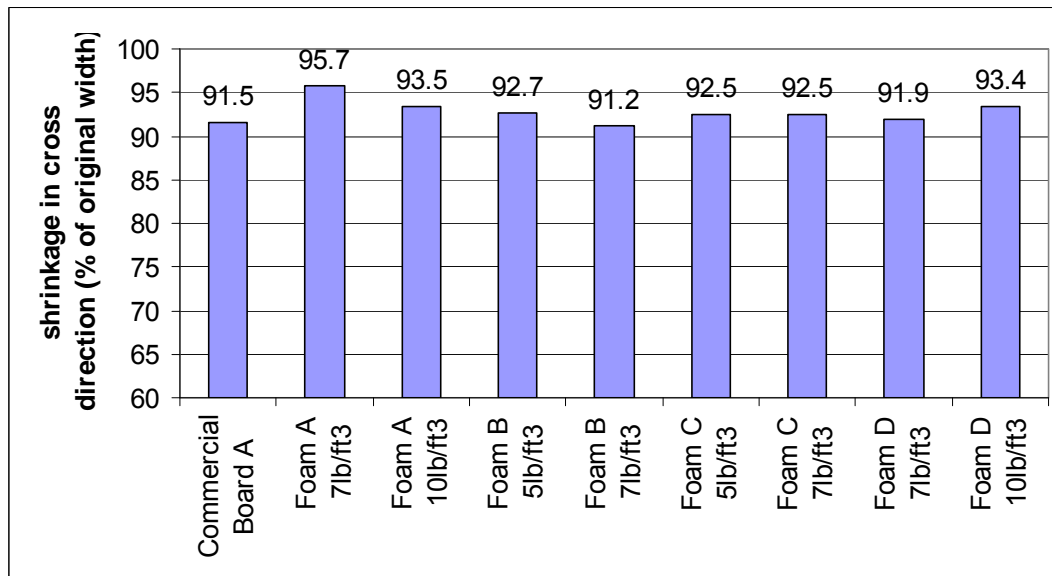

Figure 28 – Shrinkage in cross direction of fired samples

One particular cross direction measurement, Foam A 7lb/ft^3 produced less cross direction shrinkage than its counterparts. This behavior should likely be reviewed as it would seem unlikely that this particular sample would measure similarly to the others in the series for both thickness and machine direction shrinkage but different in only the cross direction. In general it is again confirmed that foam likely has little effect on fire resistance shrinkage.

The dimensional shrinkage response of the commercial sample in general showed less

"squareness" between the machine and cross directions but the average of both directions result in similar numbers. This behavior is likely due to the formation of lab board samples under less vigorous conditions which are possibly more likely to apply a bias in the direction of the production line.

Figure 29 shows an example of the surface of fired sample after cooling. Similar digital photos of the fired samples were taken and analyzed using an image analysis software package. Images were thresholded to highlight surface cracks. The area of the image that these features represented as a fraction of the entire image is presented in Figure 30.
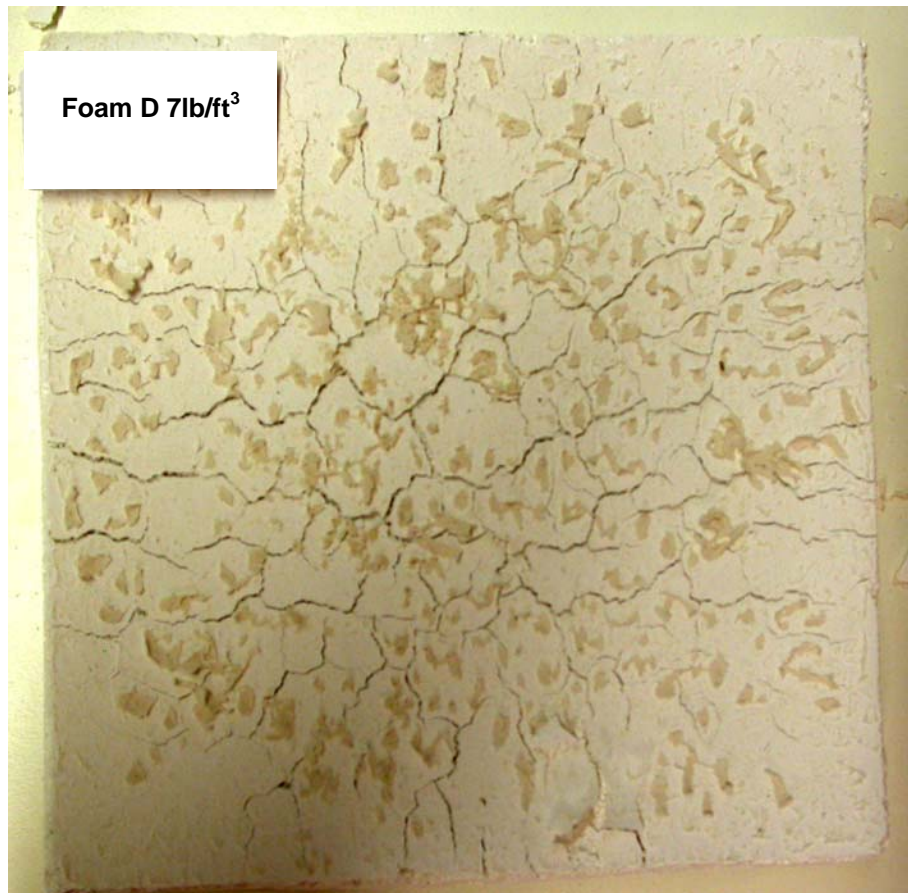

Foam D 7lb/ft^3

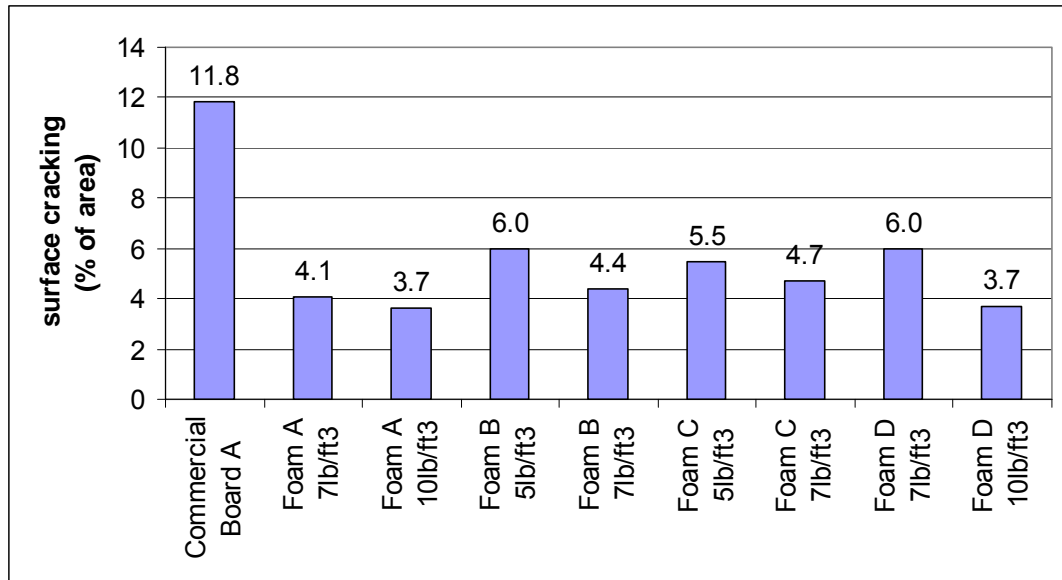*Figure 29 – Example fired board sample after cooling*

Figure 30 – Surface cracking of fired samples

Surface cracking was again relatively consistent amongst the lab board samples but was clearly less than the commercial board sample. This behavior had been previously observed and is thought to perhaps be a function of the way that commercial boards are formed in a high speed line with perhaps a less homogenous mix than the small volume of a batch scale lab mix. Again, gypsum purity and associated impurities may also play a role as the source gypsum material for the commercial sample is different than that of the moulding plaster used for consistent lab board sample production. In general, foam likely has little effect on fired board surface cracking.

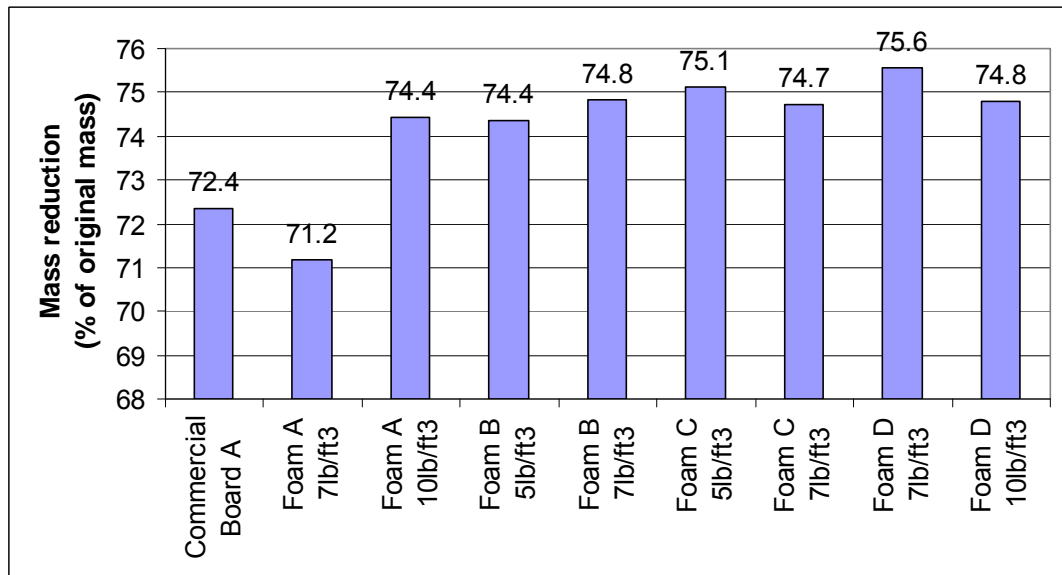The change in mass of the samples as a result of firing is presented as Figure 31.

Figure 31 – Mass reduction of fired samples

A strange result was again observed for Foam A 7lb/ft^3 highlighting a potential issue with this sample. All other lab boards generally lost similar amounts of weight on a percentage basis which would be expected for boards of similar weight made with the same purity plaster. The

commercial sample showed a higher degree of weight loss which was likely due to having a different purity than the lab samples and likely a different paper weight than the lab board samples.

8. Nail Pull Testing

Nail pull testing as per ASTM C473 (CSA A82.27) was measured for the laboratory made boards. Tests are performed measuring force (N or lbs) as an equivalent nail head geometry is advanced through the thickness of a sample. Results are reported as the maximum force encountered during the experiment. One sample was required for each test (8 total)

Again, duplicate lab boards were made with board weights as indicated in Figure 32.
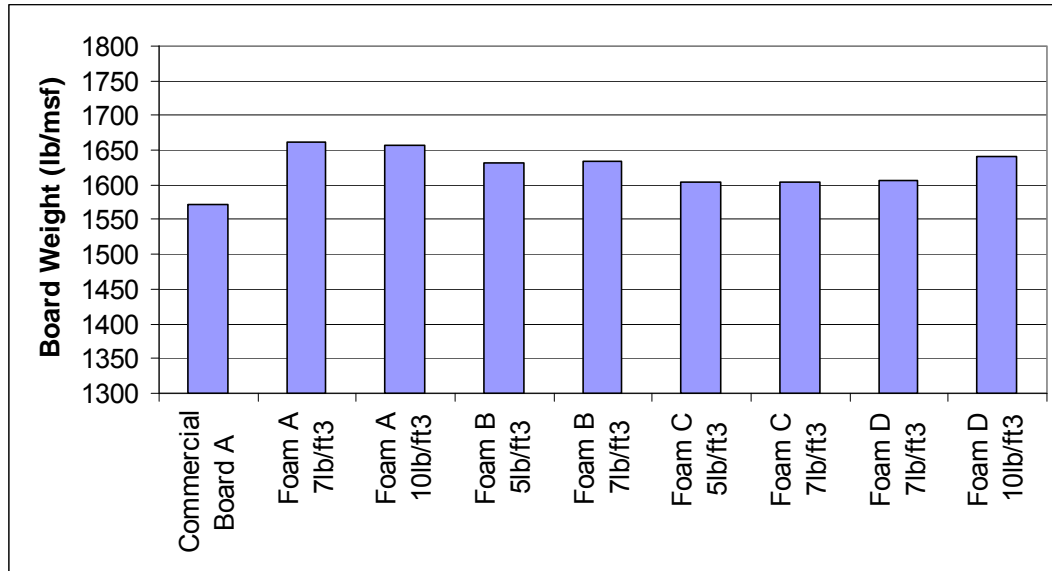

Figure 32 – Board weights of nail pull samples

Nail pull was tested on 6" square samples humidified to constant weight at 50% humidity. Results are included in Figure 33.
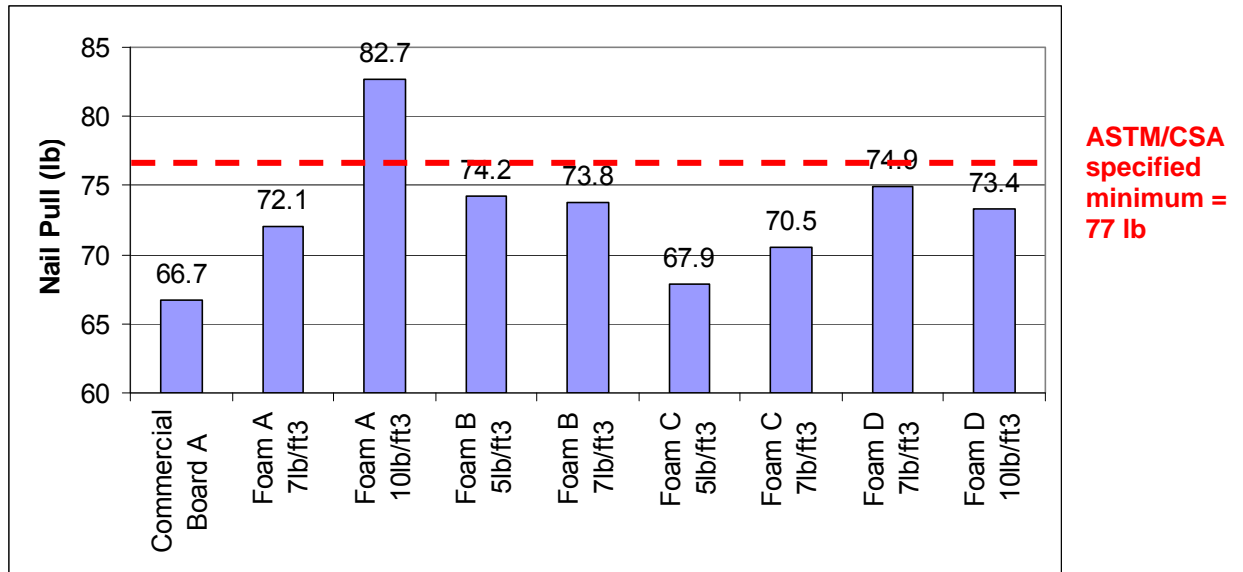
Figure 33 – Nail pull results

As expected, nail pull measurements were highly variable, with even the commercial sample not meeting the required ASTM/CSA specification minimum of 77lb. Only one board did pass the spec, Foam A 10lb/ft3.

These results were replotted as a function of board weight to determine if the nail pull responses observed are simply a reflection of how much gypsum is present overall and not necessarily the bubble structure. (See Figure 34) Those samples which were equivalently measured with CT scanning are indicated with white outlines.
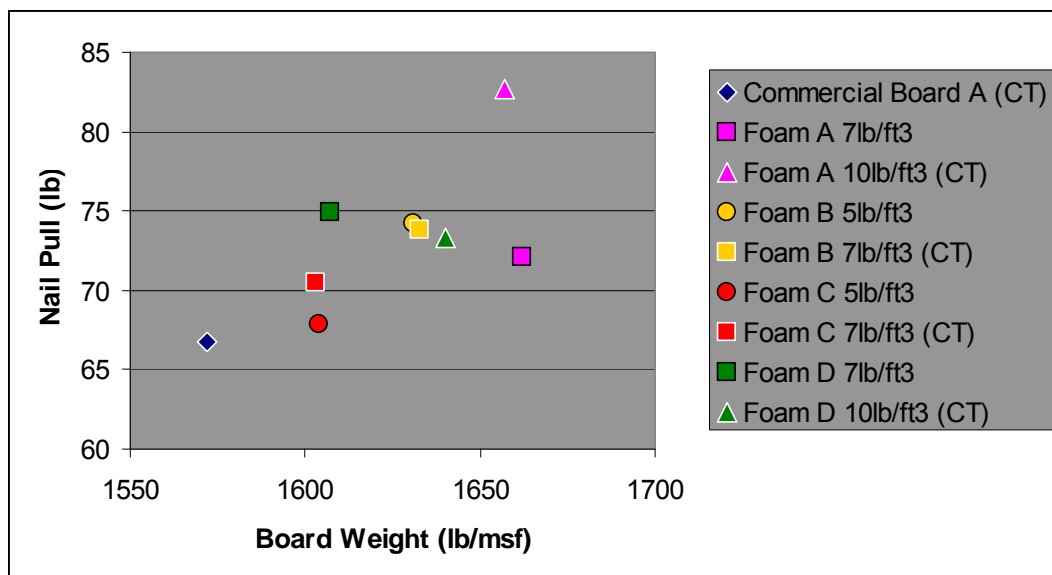

Figure 34 – Nail pull versus board weight

These results generally showed a systematic response of increasing board weight giving mostly increased nail pull results. Because only one sample of each board was measured for nail pull it is likely difficult to conclude firm absolutes from the observed behavior. For 2 of the 4 foams (Foam A and Foam C), with equivalent foaming agent the heavier foam density tended to result in improved nail pull performance at similar board weights. For 1 of the 4 foams (Foam B), foam

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density had no noticeable effect. Differences between foaming agents themselves were difficult to judge as in 2 cases (Foam A and Foam D) the different foam densities provided largely different results, yet at least one of these results from each were amongst the best results observed overall (Foam A 10lb/ft^3 and Foam D 7 lb/ft^3). Foaming agent B (and perhaps foaming agent C) gave the most reproducible results, mostly independent of foam density.

The light board weight but poor nail pull performance of the commercial sample is of ongoing concern to the gypsum industry where manufacturers optimize their products to reduce production costs with less raw material and energy use while also providing easier to use lighter panels that may simply not be as strong as is specified. Simply increasing board weights to 1600 lb/msf would likely result in more leeway in being able to pass the nail pull test but of course would problematically increase the cost to produce board and result in a product that is more difficult for installers to use. This is not a viable option for most North American manufacturers, thus a significant R&D effort has been undertaken by many of the larger producers and their additive suppliers to produce "engineered" core structures that give superior strength performance at reduced board weights.

This project as completed indicates that the representative foaming agents available to use for gypsum board production are generally able to produce some variety of different core structures. In addition, a somewhat positive result has been observed in that these alternate core structures do not seem to contribute to any benefit or detriment to fire resistance performance as determined by shrinkage and surface cracking measurements. A more neutral result was observed for the effect of core structure on nail pull performance whereby it is shown that the most unique structure as measured by CT (Foam D 10lb/ft3) did not show dramatically different performance in nail pull from the other samples measured. Similarly, the best performing nail pull sample (Foam A 10lb/ft3) did not have a particularly unique structure as compared to the similar bubble size distributions of the other boards that did not perform as well. In general it is likely recommended that the nail pull portion of this project be repeated to confirm that the nail pull results as presented are repeatable through more sample measurement.

9. Conclusions

Creating the foam generation system was more complicated than originally anticipated due to the inconsistent flow output of the original design. This shortcoming was compensated for with precision metering equipment.

Cube production with continuously generated foam was straightforward with the target weights being achieved for all planned mixes. Confirming the mixes with batch foam generation showed a large range of produced weights despite equivalent formulation, likely due to the inability of the batch mixer to entrain enough air.

Board sample production from the same mixes resulted in consistently heavier board weights than those predicted from the cube equivalent board weight numbers. This is likely a result of the higher degree of surface contact that boards experience during formation.

The boards produced were CT scanned using low resolution to remove some samples from consideration that did not have homogenous "good" cores. The four samples chosen for further evaluation were scanned at a higher resolution which identified observable differences in the bubble structure of each sample.

Of the high resolution scanned boards, Foam D 10lb/ft^3 showed a significantly reduced overall number of bubbles and on average had a larger bubble size with a broad distribution. The remaining 3 boards had similar smaller bubbles of a tighter range of distribution. Z-density profiles were mostly uniform throughout the thickness with the exception being Foam B 7lb/ft^3 which likely had skewed results due to some higher density banding throughout the thickness possibly due to improper mixing. Recrushing the core for gypsum phase analysis is a possibility to determine if improper mixing/hydration had occurred.

Fire resistance shrinkage and surface cracking characteristics were not noticeably affected by changes in the core structure.

Nail pull resistance generally tracked with increasing board weights as might be expected but did not likely correlate with the core structure as was postulated. The most unique structure produced (Foam D 10lb/ft^3) generally resulted in an average nail pull result but one of the seemingly ununique structures (Foam A 7lb/ft^3) resulted in a very good nail pull result. One board produced with Foam D at a lower weight (7lb/ft^3) may have had a positive nail pull result for the given density but this board was unfortunately not fully studied with the high resolution scans. In general, more samples produced and measured for nail pull is likely necessary to form any absolute conclusions about the effect of structure.

10. Recommended Suggestions For Future Work

As industry manufacturers develop and produce gypsum boards with differing void structures in order to reduce costs, the housing industry must pay careful attention that the accepted specification of use and functionality is maintained. It is suggested that future work in this area could include:

- To repeat board sample production and nail pull measurements of the same samples which were already characterized by high resolution scanning. Perhaps 5 samples of each.
- To evaluate a larger selection of commercial samples from across Canada
- To determine the effect of non-spherical bubbles on nail pull.

11. Potential Effects Of This Research on Canadian Housing

Of all gypsum board manufactured in Canada in 2004, approximately 91% was used locally. Approximately 60% of this board is used in residential housing, either in new homes or in renovation projects. A surprising lack of focus is placed on the fire resistance properties of 1/2" normal gypsum board which is the main gypsum product used for residential interior walls. In general, gypsum boards are used specifically for fire resistive properties but specified performance in this regard is largely only applicable to commercial products like Type X or Type C formula boards. One purpose of this project was to determine if changes in core structure technology that have been described in recent patent literature and even are beginning to be observed in commercial products, actually affect the expected fire resistance of 1/2" normal boards. Although full scale fire testing is the ultimate measure of this performance, likely valuable information can be gained from observing dimensional changes in small board samples, subject to similar temperature conditions. It was determined that no obvious benefit or detriment to fire resistive performance was observed as a result of different core structures.

Nail pull performance is another important industry measurable of 1/2" normal board. Competition in the industry has driven board weights lower and lower, but nail pull performance is known to improve with increasing board weight and is suggested to improve with larger void structures at equivalent board weight. Some recent patent literature has indicated that heavier foam densities used in gypsum board production can result in larger voids and therefore improved nail pull performance. The second main purpose of this project was to determine if changes in core structure can affect nail pull performance as described. It was determined that although different structures were able to be reproducibly generated, insufficient correlation between unique core structures and improved nail pull performance was observed. It is likely that the core structures as characterized by CT scanning were sufficiently evaluated but that more samples are necessary to fully understand the representative nail pull performance of that given structure.

Acknowledgements

Mark Flumiani   Bob Bruce   Tom Elliot

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