Performance Comparison of Bio-based Thermal Insulation Foam Board with Petroleum-based Foam Boards on the Market

Nadir Yildirim *

A process is described for developing bio-based foam board using state of the art freeze-casting technology. The bio-based thermal insulation foam board was produced starting from wood-based cellulose nanomaterials (CNs) water suspensions. Its performance properties were compared to the current products on the market: Foamular® 150 (F150), Styrofoam™ brand square edge insulation (SF), and GreenGuard® XPS (GG). The bio-based foam board's density was 0.1 g/cm^3 with an 8.16% coefficient of variation (CV), which was higher than F150's density (0.03 g/cm^3 with 0.35% CV), SF's density (0.04 g/cm^3 with 3.79% CV), and GG's density (0.04 g/cm^3 with 0.03% CV). The insulation value (R-value) was determined as 3.14 (1.47% CV) for bio-based thermal insulation foam board, 4.37 (0.39%) for F150, 4.43 (0.39%) for GG, and 5.59 (1.55%) for SF. The mechanical performance of the bio-based thermal insulation foam board was lower than those of the current products on the market, so that it requires further enhancement before potential commercialization. However, being among the first nanocellulose thermal insulation foam boards currently available, it still has great potential for use in building systems.

Keywords: Building material; Nanocellulose; Bio-based; Foam board; Thermal insulation; Mechanical performance

Contact information: Assistant Research Professor, Bursa Technical University, Bursa, Turkey;
** Corresponding author: nadir.yildirim@btu.edu.tr*

INTRODUCTION

The environmental, economic, and political impacts of energy production and use are an area of great concern. One of the most prominent uses of energy is the heating and cooling of buildings. Thus, construction companies are continually searching for ways to improve the insulation performance of the building envelope. However, the rigid foam board insulation products in widespread use today are produced from petroleum-based chemicals (Cervin *et al.* 2013) that emit high levels of carbon during production. The materials also cannot be reused or recycled.

From 2008 to 2013 there was a significant increase in the insulation market, and global demand for insulation is projected to be nearly 26 billion square meters of R-1 (thermal resistivity) value in 2020 (The World Insulation Market 2016). This mirrors impressive growth in building construction activity. In North American residential construction applications alone, demand is projected to grow over 5% annually (The Smart Market Report, World Green Building Trends 2016).

Polystyrene represents approximately 8% of the global insulation market (The World Insulation Market 2016). The insulation market is well-established and has been home to much innovation during the past 50 years as new materials have been developed. Improvements have ranged from the development of improved paper insulation products to the invention of new foam boards. The bio-based thermal insulation foam board developed in this study offers a direct replacement for the petroleum-based rigid thermal insulation products that currently constitute the largest portion of the rigid insulation board market. The U.S. Department of Energy (DOE; US DOE 2017) data on the primary competitive products are shown in Table 1.

Table 1. Primary Competitive Products on Market

Type	Insulation Materials	Applications	Installation Method (s)	Advantages
Foam Board	Polystyrene	• Unfinished walls	• Interior applications	• Good Insulating
	Polyisocyanurate	• Foundation Walls	• Exterior Applications	• Energy cost reduction
	Polyurethane	• Low Slope Roofs		

In addition to these petroleum-based products (Table 1), there have been many studies focusing on developing rigid and flexible green insulation products. Researchers have focused on design of flexible polyurethane foams using lignin-like waste residue obtained from *Arundo donax* L. (Bernardini *et al.* 2017). They successfully produced *A. donax* residue-based open-cell foams. Also, cork based insulation products exist on the market. Researchers compared the prices and the performances of the cork based products (Corecork NL10, Corecork NL20, Divinycell H60) and showed that the Divinycell H60 foam, which is the least expensive, also has the lowest mechanical performance properties (Urbaniak *et al.* 2017). Tondi *et al.* (2016) manufactured lignin foams in different densities as an alternative for traditional insulation materials (Tondi *et al.* 2016). These studies reveal strong interest in green thermal insulation products for use in building systems.

In this research, a bio-based foam board for thermal insulation was developed, characterized, evaluated, and compared to current commercially available thermal insulation foam boards.

The bio-based foam boards were developed using mechanically produced nanocelluloses. The first successful mechanical production of nanometer scale cellulose was in the 1980's when a research group passed a wood pulp suspension through a homogenizer several times, resulting in a gel-like suspension of highly fibrillated cellulose that was named microfibrillated cellulose (MFC) (Turbak *et al.* 1983). This process involved forcing the material through a small capillary to break fibers apart. This requires high pressure to allow the wood fibers to break down from 30 µm to a size of 20 nm to 50 nm in diameter. Other mechanical methods have been reported, such as microfluidization, micro-grinding, refiners, and cryocrushing. Today, the nanoscale material generated through the mechanical process is often called nanofibrillated cellulose (NFC) or cellulose nanofibrils (CNF) (Turbak *et al.* 1983; Revol *et al.* 1992). The advantages of mechanical methods are high yield and the absence of chemical costs and chemical disposal costs.

This study concentrated on creating a novel bio-based foam board for use in the construction industry and comparing its performance properties with the current petroleum based products on the market.

EXPERIMENTAL

Materials

In this study, a bio-based foam board for thermal insulation purposes was created using biodegradable polymers that have low thermal conductivities and satisfactory mechanical properties. Then, the developed novel bio-based foam board was evaluated and compared with the current products on the market. Three commercialized products: Foamular® 150 (F150) (Owen's Corning, Toledo, OH, USA), GreenGuard® (GG) (Lowes, Mooresville, NC, USA), and Styrofoam™ brand square edge insulation (SF) (Dow, Midland, MI, USA), were tested, evaluated, and compared with the bio-based foam board developed in this study.

The manufacturing process began with a nanocellulose, obtained from the University of Maine (Orono, ME, USA) and water suspension that was placed in trays. An industrial corn starch was added to the suspension after being cooked for 1 h at 90 °C to provide crosslinking (Yildirim *et al.* 2014). The obtained gel-like suspension was then placed into a freeze-dryer (SPScientific 25ES; SPScientific, Warminster, PA, USA). Next, thermocouples were placed in the material to monitor the temperature during the freeze-drying process (Fig. 1).

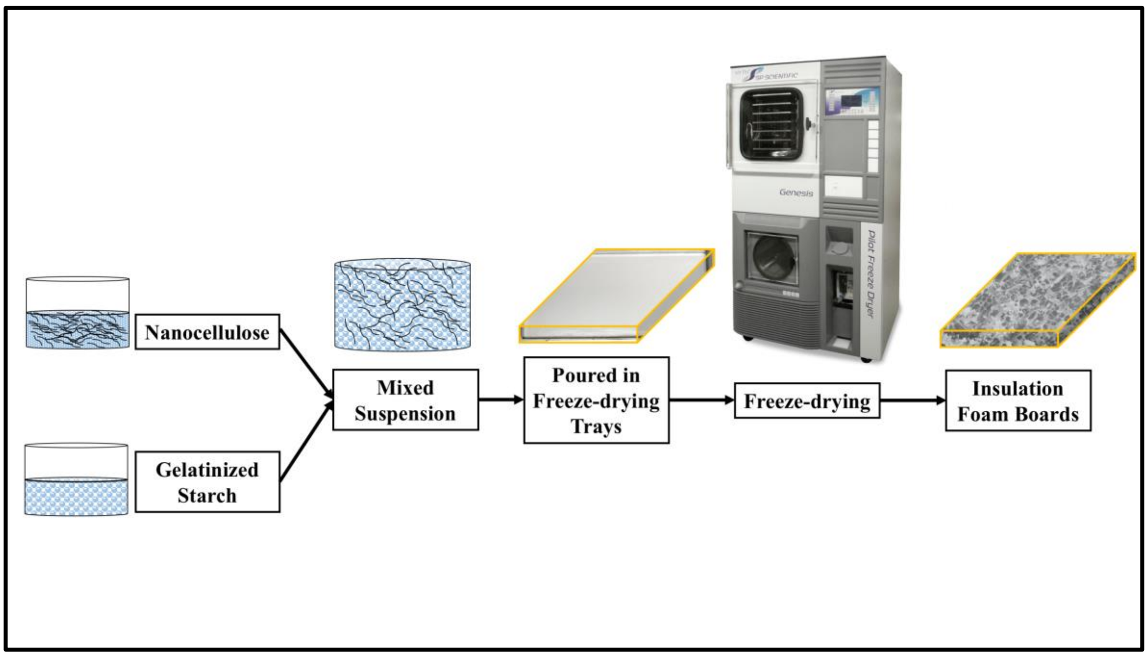

Fig. 1. Bio-based thermal insulation foam board manufacturing process

A partial vacuum was then employed to prevent ambient moisture from entering the freeze-drying chamber. The chamber temperature was lowered from 20 °C to -20 °C over 2 h and maintained at that temperature for 240 min. The chamber was then evacuated to a pressure of 150 mTorr. The chamber temperature was maintained at -20 °C for 240 min, raised to 0 °C over 2 h, raised to 20 °C over 4 h, and then maintained until the average thermocouple reading of the materials was 20 °C for 4 h. The trays were then pulled out, and the foam boards were stored in the laboratory for at least 24 h prior to testing.

Methods

Physical properties

Density measurements were obtained according to ASTM C303 (2010) by taking different dimensions of the whole panel and averaging them together. The mass of the panel was then measured with the Sartorius MA37 moisture balance with 0.001 g readability. The measured mass (g) was divided by the measured volume (cm^3) to identify the density.

Mechanical properties- Flexural testing

A total of six 7 in × 3 in × ½ in samples were prepared from each group. These samples were tested according to the ASTM C203 (2012) standard using the 3-point bending test method. The cross-head displacement rate was 0.12 in/min. Specimen displacement was obtained from the crosshead displacement (Instron 5500R; Instron, Norwood, MA, USA). The flexural tests were performed under laboratory conditions (25 °C ± 2 °C and 50% relative humidity). The flexural modulus was calculated using the linear portion of the force-displacement curve, and the maximum flexural strength was also found.

Compression testing

For compression testing, six 4 in × 4 in × ½ in samples were prepared from each group. Each specimen was compressed at a rate of 0.05 in/min. The specimen displacement was obtained from the cross-head displacement (Instron 5500R; Instron, Norwood, MA, USA). Compression tests were conducted under laboratory conditions (25 °C ± 2 °C and 50% relative humidity).

The compressive modulus was calculated using the linear portion of the force-displacement curve, and the maximum compressive strength was also found.

Thermal properties- Thermal conductivity measurements

A total of eight 6 in × 6 in × ½ in samples were made from each group. The samples were tested according to the ASTM C518 (2010) standard using a heat flow meter (NETZSCH Lambda 2000 heat flow meter, NETZSCH Instruments, Burlington, USA). The thermal conductivities, and thus the insulation values (R-values) of the samples, were found and compared.

Statistical analysis

In this study, JMP Statistical Analyses Software (SAS, Cary, NC, USA) was used. The density, compression, flexural and modulus strength, thermal conductivity, and thermal resistivity analysis data were compared by conducting a one-way means/analysis of variance (ANOVA) to check if there was a significant overall difference (significance level (alpha) = 0.01) between the groups (Bio-based foam board, F150, GG, and SF). Significant differences between groups were evaluated with a Tukey-Kramer Honestly Significant Differences (HSD) test with alpha = 0.05. A sample size of six (n = 6) was used for all statistical analysis.

RESULTS AND DISCUSSION

The bio-based thermal insulation foam board was successfully manufactured using nanocellulose (Fig. 2) as the raw material.

Fig. 2. Bio-based thermal insulation foam board

The developed bio-based foam board had a statistically different density from the other products. Statistical differences were observed between the F150 and SF, and the GG showed no statistical difference between the F150 and SF. A large range was obtained in the developed and commercial products' densities (0.04 g/cm^3 to 0.1 g/cm^3). The density, flexural modulus (elastic modulus), and flexural strength (MOR) of the foams are summarized in Table 2.

Table 2. Flexural Properties of Foams

Sample	Density (g/cm^3)	Elastic Modulus (kPa)	Modulus of Rupture (kPa)
Bio-based foam board	0.100 (8.16) A	15082.64 (3.48) B	229.50 (7.77) C
F150	0.03 (0.35) C	21610.18 (1.78) B	497.82 (3.27) A
GG	0.04 (0.03) BC	18454.16 (5.09) B	317.86 (1.26) B
SF	0.04 (3.79) B	65915.39 (27.60) A	391.09 (19.32) B
* Parentheses indicate the coefficient of variation (COV,%); A, B, C, and D indicate the significant differences between the treatments			

The density of the bio-based foam board was similar to results reported by other studies. Wicklein *et al.* (2014) developed a thermal insulation composite foam board using CNF, and they found the density was 0.075 g/cm^3 for their product. The usage of less solid content in the starting materials produced a lighter final product, as expected.

The flexural strength of the bio-based foam board was statistically lower than the F150, GG, and SF. In previous literature, it was shown that the increase in density produced better mechanical performances (Yildirim *et al.* 2014; Nikolina 2016). However, this phenomenon is only valid when a comparison of the products' compositions are the same or very similar. In this study, the manufacturing process had an important effect on the weakness of the final product. The bio-based foam boards were produced through a random, natural drying process, in which the pores could have a large variety of diameters. In addition, the columns and walls between the pores could have imperfections and could fail easier and faster under external loads. The commercialized products were produced using a controlled manufacturing process, which produced a well-organized hierarchal structure that showed improved resistance against external loads.

The compression performance of the foams (Table 3) showed a trend consistent with that found for the flexural behavior. However, a comparison of the compression properties (Table 3) showed that the bio-based foam board's compression performance appeared promising for applications, such as insulation and packaging.

Table 3. Compression Properties of Foams and Comparisons with Other Studies

Sample	Density (g/cm^3)	Compression Modulus (kPa)	Compressive Resistance (kPa)
Bio-based foam board	0.100 (8.16) A	1092.93 (15.03) B	169.97 (6.98) B
F150	0.03 (0.35) C	3803.43 (23.69) A	224.36 (5.82) A
GG	0.04 (0.03) BC	1859.62 (11.4) B	226.52 (0.80) A
SF	0.04 (3.79) B	2596.25 (4.44) AB	213.05 (1.86) A
Parentheses indicate the coefficient of variation (COV,%); A, B, and C indicate the significant differences between the treatments			

Wicklein *et al.* (2014) also investigated the mechanical performances of the CNF composite foam boards that they developed. They found the Young's modulus to be 570 kPa, which is lower than the modulus value (1093 kPa) of the product developed in this research. This difference was due to the higher density value of the foam board that was developed in this research.

Ali and Gibson (2013) found a 1760 kPa compression modulus for the foam board that they developed using CNF. The higher amount of CNF used in their foam board produced a higher mechanical performance than the product developed in this study (Ali *et al.* 2013).

Berglund *et al.* (2016) produced microfibrillated cellulose (MFC)-xyloglucan (XG) foams with the composition ratio (MFC/XG) changes of 100/0 to 90/10 and 80/20 to 70/30. They found that increased XG provides higher modulus values. According to their findings, the overall modulus values varied between 440 kPa and 1470 kPa (Sehaqui *et al.* 2010), which is also comparable with this research.

The authors did not find a statistical difference between the F150 and GG's thermal conductivity values. The SF was determined as the best insulation product compared to the other products compared (Table 4).

The commercial products of F150, GG, and SF that were tested and evaluated in this research showed similar results with the previous studies. According to Mahlia *et al.*'s study, some of the current thermal insulation materials used on the market have the following thermal conductivity values: fiberglass-urethane (0.021 W/m-K), fiberglassrigid (0.33 W/m-K), urethane-rigid (0.024 W/m-K), extruded polystyrene (0.029 W/m-K), and urethane (roof deck) (0.021 W/m-K) (Mahlia *et al.* 2007).

Table 4. Thermal Conductivity and Thermal Resistivity Properties of Foams

Sample	Density (g/cm³)	Thermal Conductivity (W/m-K)	R-value (°F.h.ft²/BTU)
Bio-based foam board	0.100 (8.16) A	0.045 (0.88) A	3.14 (1.47) C
F150	0.03 (0.35) C	0.033 (0.69) B	4.37 (0.79) B
GG	0.04 (0.03) BC	0.033 (0.39) B	4.43 (0.39) B
SF	0.04 (3.79) B	0.026 (1.56) C	5.59 (1.55) A
Parentheses indicate the coefficient of variation (COV,%); A, B, and C indicate the significant differences between the treatments.			

The bio-based foam board produced in this study showed promising thermal conductivity and resistivity results, such as its compression and flexural properties. Similar results were reported in other studies. Kwon (2012) found that the thermal conductivity values ranges between 0.034 W/m-K and 0.038 W/m-K for the cellulose foams that they developed. The foams produced in this research showed higher thermal conductivity properties, which were explained by the higher density of the developed foam boards. A higher density is related to the solid content in the materials, which allows thermal conductivity to occur faster than in pores. Additionally, air-based insulation, such as the one developed in this study, cannot exceed the R-value of the air. However, petroleum-based thermal insulation foam boards use fluorocarbon gas in the insulation cells, which results in higher R-values (Al-Homud 2005).

The literature and the current study showed that the bio-based thermal insulation foam board had higher thermal conductivity values than current products on the market. However, foam board still has promising properties that can be modified and enhanced to create an optimal bio-based thermal insulation foam board. This bio-based foam board will not only provide similar performance properties but also provide an eco-friendly, sustainable thermal insulation foam board and decrease the carbon footprint.

CONCLUSIONS

1. The major conclusion of this study is that the nanocellulose as a raw material was found suitable for developing innovative products for the construction and building industry.
2. The bio-based foam board density was 0.1 g/cm^3 with an 8.16% coefficient of variation (CV), which was higher than F150's density (0.03 g/cm^3 with 0.35% CV), SF's density (0.04 g/cm^3 with 3.79% CV), and GG's density (0.04 g/cm^3 with 0.03% CV).
3. The insulation value (R-value) was determined 3.14 (1.47% CV) for bio-based thermal insulation foam board, 4.37 (0.39%) for F150, 4.43 (0.39%) for GG, and 5.59 (1.55%).
4. The F150 showed the highest compression modulus and no statistical difference were observed between the bio-based foam board, GG, and SF.
5. The SF showed the highest elastic modulus value, and no statistical differences were found between the bio-based foam board, F150, and GG.
6. The bio-based foam boards could be used for insulation purposes in building systems.

7. The developed bio-based foam boards could be potentially commercialized through the enhancements in performance properties.
8. This bio-based product could be a useful alternative to be used in green building projects.

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