Investigation of a Novel Insulation Foam Made from Gypsum Drywall Waste

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ABSTRACT
Foamed plastic rigid insulation panels are effective for reducing building heating and cooling loads, with consequent reductions in energy use and associated greenhouse gas (GHG) emissions. However, plastic foam manufacturing and in-service use result in significant GHG emissions. In addition, plastic foams are flammable, and have been implicated in recent building fires. This paper describes proprietary mixtures and methods for producing drywall waste foam (DWF) panels, a carbon-neutral, fire-protective insulation made from gypsum drywall waste and other construction and demolition (C&D) waste materials. Gypsum drywall waste is inherently fire-protective and has relatively low thermal conductivity, but is a low-value commodity with few current reuse and recycling applications. DWF panels address two pressing issues in the built environment: decarbonization of building materials, and diversion of problematic C&D waste from landfills. Investigation of DWF panel engineering properties, including density, hardness, friability, burn-through time, and thermal conductivity are reported, with results compared to analogous commercially-available materials. Potential applications and areas for future investigation are also discussed.

KEYWORDS
New technologies & materials; Fire protective insulation; Construction & demolition waste; Drywall recycling; Waste paint.

INTRODUCTION
The research reported here aimed to develop novel, fire-protective thermal insulation panels made from waste products of building construction and demolition (C&D) and other waste materials. This novel insulation was developed in response to a need identified by industry for new, non-combustible insulation materials (STO, 2018), as well as an identified need for new applications for recycled gypsum drywall waste, a problematic C&D waste material (King County, 2017).

As a component of well-designed building envelope assemblies, thermal insulation plays an important role in reduction of greenhouse gas (GHG) emissions associated with direct or indirect use of fossil fuels to meet building heating and cooling loads. Thermal insulation reduces conductive and convective heat transfer between conditioned spaces and the exterior environment, typically through small-scale cells of air or other low-conductivity gases trapped in a fibrous or foamed matrix, and the resistance to heat transfer of a given insulation material depends on a number of factors, including: thermal conductivity of the matrix material and the trapped gas; material density and cell size; moisture content; and others (Anh and Pasztory, 2021).

Limitations of current high-performance thermal insulation materials commonly used in on- and off-site building constructions, especially foamed plastics such as extruded polystyrene (XPS), expanded polystyrene (EPS), and polyisocyanurate (PIR), include production and in-service GHG emissions far more potent than CO_2 (Mazor et al., 2011). Additionally, in a fire event continuous exterior layers of flammable plastic foam insulation can result in stack effects (Guillaume et al., 2019). Furthermore, combustion of PIR foams produces toxic hydrogen cyanide (McKenna and Hull, 2016).

Our previously published work disclosed mixtures and methods for producing masonry units made from gypsum drywall waste. These units were found to have high insulation value compared to conventional masonry, due in part to the relatively low thermal conductivity of gypsum (Drake and Miyasaka, 2020). Further, the gypsum component in drywall waste (calcium sulphate dihydrate: $CaSO_4{\bullet}2H_2O$) is non-combustible and fire protective, due to molecularly-bound water of hydration (Crangle, 2017). We therefore hypothesized foamed mixtures of drywall waste and other waste materials would produce a novel rigid insulation with superior fire-protective properties. Following successful development of proof-of-concept Drywall Waste Foam (DWF) specimens, we investigated engineering properties of different formulations of the new material.

Precedents in literature

Non-combustible foamed insulation. Foamed cast-in-place concrete and precast foamed concrete blocks have a long history of use with patents dating to the 1920s (Hebel, 2022). Foamed concrete is non-combustible, but thermal performance is inferior to conventional insulation materials (Ahn and Pasztory, 2021). Moreover, foamed concrete mixtures require significantly higher proportions of PC than conventional concrete, increasing the material's carbon footprint (ASTM, 2007).

Drywall waste generation and applications for reuse. Gypsum drywall panels are inexpensive, inherently fire resistant, and widely used as an interior finish material in both residential and commercial construction. Installation of new drywall results in 10-12% waste (Crangle, 2017). Building demolition produces higher volumes of drywall waste than construction, accounting for about 70% of the drywall waste stream (EPA, 2020). In 2018, the most recent year for which figures are available, some 12 million metric tons of drywall C&D waste were landfilled in the United States alone, approximately 9.2% of landfilled building C&D waste (EPA, 2020) (Figure). Under landfill conditions, sulfate-reducing bacteria metabolize drywall waste and produce hydrogen sulfide gas (H_2S). At low levels, H_2S is detectable as an offensive 'rotten-egg' odor, and has health impacts at higher concentrations (Townsend et al., 2002). Landfilling drywall waste from construction is now banned in some locations (Lederman et al. 2015; King County, 2017).

Industry studies show C&D waste recycling provides many environmental and economic benefits (CDRA, 2017). However, lack of applications for recycled drywall waste is a barrier to increased recycling. Drywall waste recyclers have unused capacity, and would like new markets for recycled drywall products (Lederman et al, 2015; CDRA, 2017).

Applications for recycled gypsum in construction have been reported. Naik et al. (2010) investigated performance of recycled drywall waste as a supplemental cementitious binder in concrete. Raghavendra and Udayashankar (2015) report use of drywall waste in controlled low strength materials (CLSM), also using drywall waste as a binder component. Raghavendra et al. (2016) investigated CLSM ternary binder mixtures of drywall waste, Portland cement, and waste-derived pozzolans including fly ash and ground granulated blast furnace slag.

METHODOLOGY

Materials, mixtures and methods

Development. The mixtures and methods reported here were developed through initial stepwise experimentation, with qualitative assessment of specimen properties to be quantified during subsequent investigations, e.g., hardness, friability, and burn-through time. This initial experimentation favored polymer binders over cementitious binders, and found liquid acrylic adhesive and waste paint binders superior to other polymer binders tested. Waste paint was selected as best aligned with the waste reduction goals of the research.

Drywall waste (DW) was sourced from local building sites and processed using a hammer mill. Cellulose fiber (CF) was derived from newsprint or cardboard sourced from local recycling centers and processed using a hammer mill. Waste acrylic and latex paints (WP) were sourced locally, and comingled before use. Solids percentage was calculated as 58% from dried samples. A non-proprietary foam agent (FA) was prepared using mixtures and methods adapted from Siva et al. (2015).

Density and structure of cured dry foam specimens was dependent on the density, structure, and stability of the wet foam generated during mixing. Wet foam qualities, in turn, were largely dependent on the following factors: foaming method used; type of binder; ratio of drywall waste to cellulosic fiber; ratio of binder to other ingredients; ratio of both foam agent and water to dry ingredients; and mixing times.

Additional qualitative observations included the following: adding CF up to about 10% of total dry weight had a stabilizing effect on the structure of the wet foam; adding additional water increased the speed and extent of foam generation, but resulted in less stable wet foam structure, longer curing times, and pronounced deformation of cured foam through shrinkage; and longer mixing times increased foam generation and lowered the density of both wet foam and cured dry foam panels.

Foam preparation, molding, and curing. For the investigations reported here, the ratio of DW to CF and the ratio of combined dry ingredients to water was held constant. Ratio of WP to dry ingredients varied across mixtures, with the FA ratio varying in inverse proportion to hold water content constant (Table 1). FA and WP were blended and combined with dry ingredients. Mixtures were foamed by mixing for 15 minutes at 140 rpm, using a Welbilt 60 liter programmable industrial food service mixer equipped with wire whisk. Foamed mixtures were poured into burlap-lined wire mesh molds, then cured and dried for a minimum of 24 hours at 93°C. Cured and dried foam billets were cut into specimens using a bandsaw equipped with a standard wood blade. All specimens were conditioned prior to testing using procedures specified by ASTM 367/367M:

Standard Test Methods for Strength Properties of Prefabricated Architectural Acoustical Tile or Lay-In Ceiling Panels.

Density. Density was calculated from specimen mass and volume, averaged across a minimum of three specimens.

Microstructure imaging. 25 mm x 25 mm areas of each specimen were imaged at 4800 dpi resolution using an Epson V850 Pro flatbed scanner, enabling 26x magnification on a 4K monitor. This proved to be a rapid and cost-effective method for initial assessment of microstructure in cured foams (Figure 1).

Hardness. Specimen hardness was determined by adapting test procedures specified in ASTM 367/367M to an available test apparatus. Descent rate of the penetrator was significantly faster than specified in the standard (12.5 mm/min vs. 2.5 mm/min), due to mechanical limits of the apparatus.

Friability. Specimen friability was determined using test procedures specified in ASTM 367/367M.

Burn-through time. An alternative test procedure for assessing specimen burn-through time was developed, due to the impracticality of lab-scale investigations using methods and equipment specified in ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials and E119: Standard Test Methods for Fire Tests of Building Construction and Materials.

Test apparatus consists of: Bunsen burner, adjustable for fuel flow and fuel:air mixture; 200 mm x 200 mm fiber-cement panel with 75 mm x 75 mm cutout; pyrometer; timer; and 47 mm x 47 mm cotton pads weighing 0.5 g each.Burner flame characteristics were adjusted to achieve consistency across tests. Specimens measuring 8 mm x 100 mm x 100 mm were centered over the panel cutout with cotton pad attached to the top surface and timer started. Timing stopped at cotton ignition. To establish comparative results, specimens of acoustic ceiling tile (AT), XPS and EPS foam were also tested.

Thermal conductivity. Specimen thermal conductivity was determined using procedures and apparatus specified in ASTM C518: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.

Table 1. Foamed mixture proportions, grams/100 grams.

Mix ID	DW	CF	FA	WP
WP50	34	4	28	34
WP43	34	4	37	25
WP33	34	4	45	17

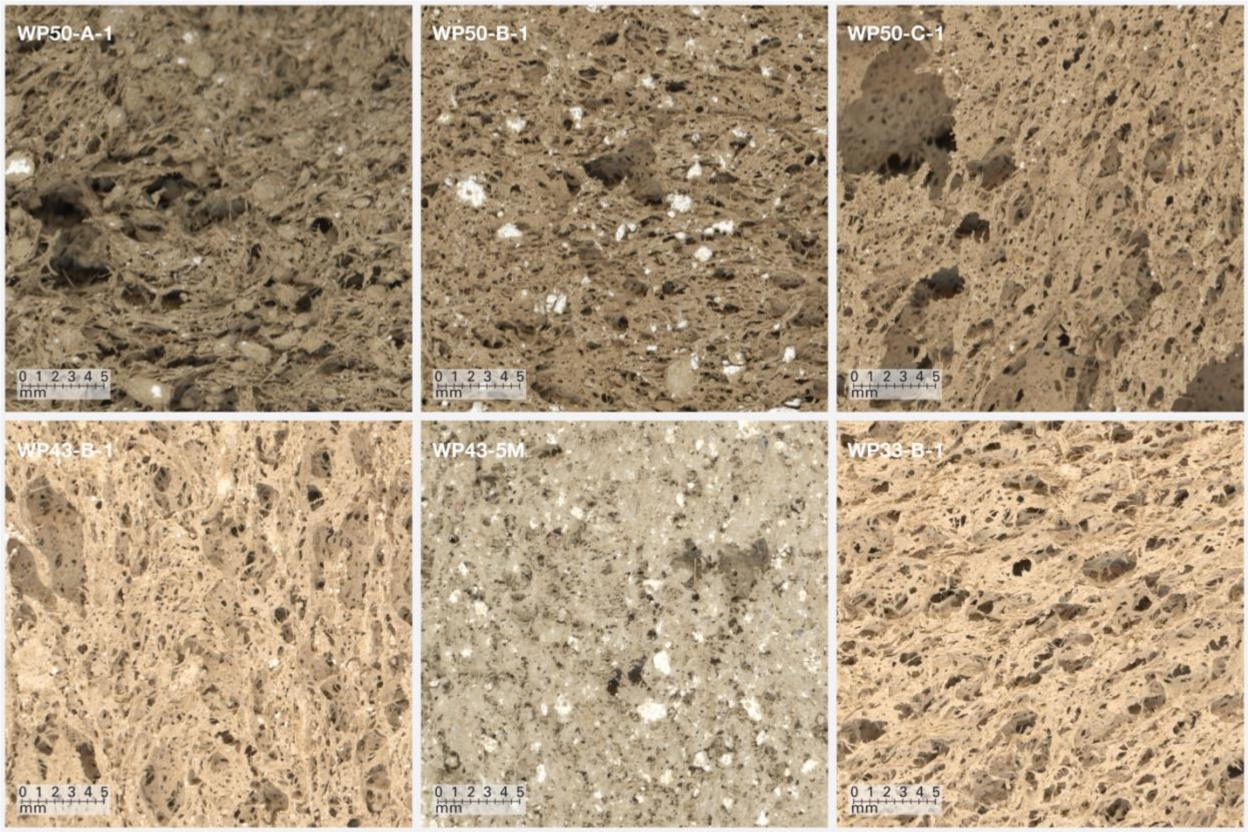

Figure 1. Microstructure of typical DWF specimens.

RESULTS AND DISCUSSION

Averaged results from test procedures are given in Table 2, including results from control specimens. From weighted ranking of results (Figure 2), foam density appears to have the clearest effect on engineering properties. Increasing foam density increases mechanical strength, as measured by hardness and friability.

Table 2. Averaged results.

Billet ID	Density (g/cc)	Hardness (kgf)	Friability (% lost)	Burn time (mm:ss)	Conductivity (W/m^{2}K)
WP50-A-1	0.25	38.7	—	—	—
WP50-B-1	0.34	70.4	39	—	0.05451
WP50-C-1	0.23	22.1	57	01:50	0.05203
WP43-1	0.18	26.2	—	—	—
WP43-B-1	0.24	21.8	52	02:22	—
WP43-5M	0.37	130.9	16	04:52	—
WP33-1	0.15	3.7	—	01:33	0.04166
WP33-X-1	0.15	21.7	—	—	—
AT	0.32	81.7	45	03:15	—
EPS	0.02	16.5	—	00:05	0.03637
XPS	0.03	35.7	—	00:08	—

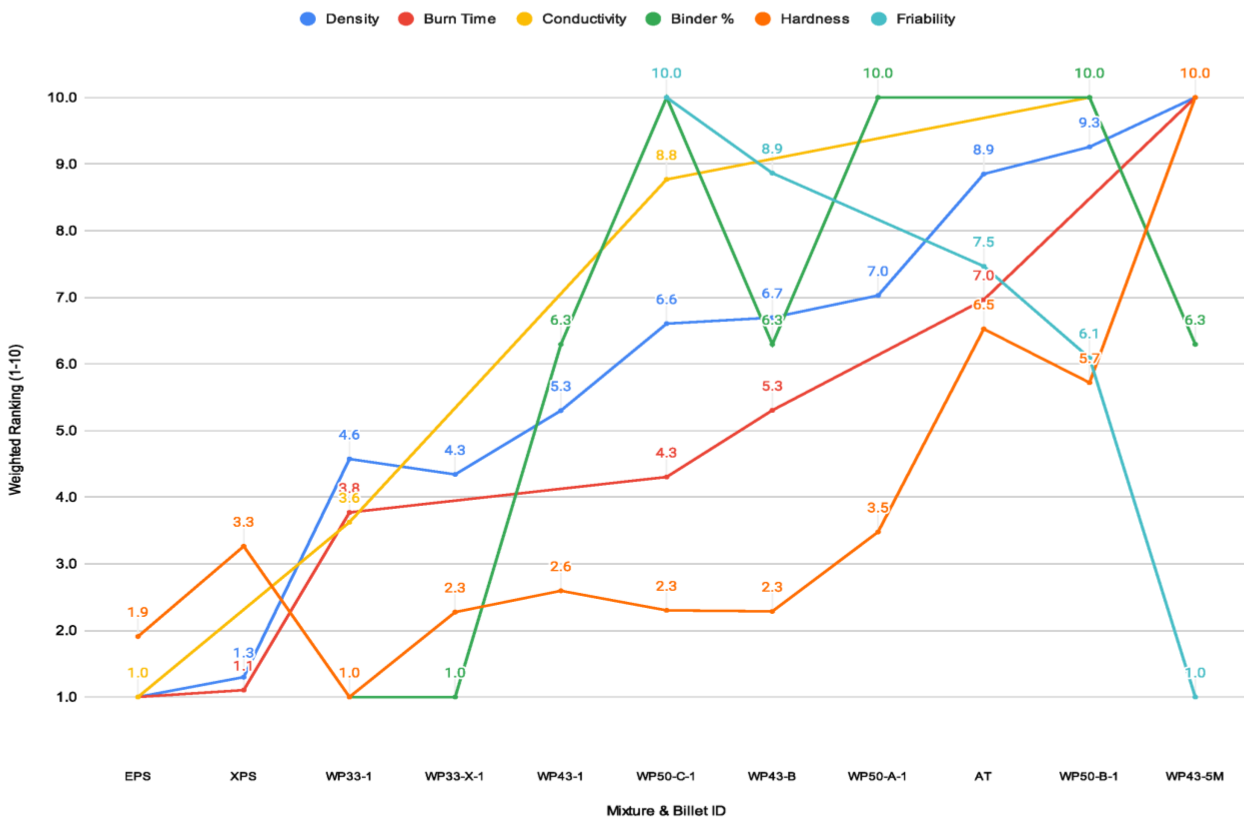

Figure 2. Comparison of mechanical properties.

Inverse relationships exist between several desirable properties. Specimens with low densities have better insulation value, due to decreased thermal conductivity, but lower mechanical strength and reduced burn-through time. Manipulating foam density through changing mixing time or changing ratios of foam agent to other ingredients may permit optimising properties for specific applications.

Although initial observations suggest mechanical properties of DWF panels are insensitive to the expected range of variations in both drywall waste and waste paint, quality control may nevertheless pose challenges. The hydrophilic nature of both the gypsum and cellulosic fiber components may limit applications versus some rigid plastic foams. However, many common cavity insulation materials also require careful detailing to avoid water infiltration. Our previous work demonstrates successful use of additives to reduce water absorption in drywall waste-based masonry; use of additives in DWF panels is an area for further research.

CONCLUSIONS

Results suggest replacing some common insulation materials with DWF rigid panels can reduce GHG emissions and contribute to circular economies by providing new applications for problematic building C&D waste. The novel mixtures and methods disclosed in this paper incorporate higher percentages of gypsum drywall waste than other drywall waste recycling applications reported in literature, such as CLSM and most other concrete drywall waste mixtures. Because there is significant overlap in materials typically used for thermal insulation and materials used for acoustic isolation, DWF panels are expected to have acoustic applications as well. In addition to mechanical properties and performance equivalent or superior to comparable existing materials, DWF specimens have fire protective qualities not found in plastic foams, with some specimens appearing to outperform fire-rated acoustic ceiling tile.

Future research.

Further investigations will broaden the range of densities tested, and extend characterization of DWF mechanical properties, including water absorption, transverse strength, compressive strength, and surface burning. It is recognized that detailed life cycle assessment (LCA) is necessary to quantify DWF panel contributions to decarbonization of the built environment.

ACKNOWLEDGEMENT

Research was supported by a Commercialization Gap Fund grant from the WSU Office of Commercialization and the Washington Research Foundation. The researchers gratefully acknowledge assistance from Vikram Yadama (WSU Composite Materials and Engineering Center), as well as from past and present WSU architecture students.

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