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Techno-economic analysis of light weight concrete block development from polyisocyanurate foam waste

Premrudee Kanchanapiya[a], Pawadee Methacanon[a], Thanapol Tantisattayakul[b,*]

[a] National Metal and Materials Technology Center, National Science and Technology Development Agency, Pathumthani, 12120, Thailand
[b] Department of Sustainable Development Technology, Faculty of Science and Technology, Thammasat University, Thailand

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ABSTRACT

Polyisocyanurate (PIR) is one of the materials commonly used as thermal insulation. With increasing global use of PIR due to its high R-values and superior fire resistance, the volume of PIR waste (PIRW) will increase over the years. Production of lightweight concrete block (LWCB) from PIRW can contribute to both efficient waste management and energy savings in air conditioning systems during the operation phase of buildings due to the insulation properties of LWCB. In this research, we determined the most suitable blends for the production of lightweight concrete mixed with PIRW (LWC-PIRW) taking into account both the technical properties and economic feasibility of LWC-PIRW production. The results show that the formula with 8% PIWR (particle size passing through sieve No. 4 and retained on sieve No. 10), 0% sand, and a water/concrete ratio of 0.7 forms a suitable composition; its compressive strength, dry density, and water absorption pass Thai industrial standards. The thermal conductivity of LWC-PIRW is 0.3598 W/m K which is similar to that of other typical foamed concretes. The economic feasibility analysis shows that the production of LWC-PIRW is economically feasible, and the sensitivity analysis shows that the return of the project is more sensitive to the selling price of the LWC-PIRW than to the production volume.

1. Introduction

Buildings are recognized as making up one of the most energy demanding sectors (Berardi, 2017). Throughout their life cycle, the energy used in the operation phase to maintain the inside environment at the desired level of comfort is the largest contributor to the energy consumption (Ramesh et al., 2010). Therefore, thermal insulation of buildings has a great potential for reducing the energy consumption in buildings. Lightweight concrete is one of the important construction materials in terms of energy efficiency as it increases thermal insulation properties and consequently decreases the thermal load passing into the building. Recently, there have been many studies regarding waste utilization in the production of building construction materials in order to save natural resources and promote environmental sustainability (Jin et al., 2015; Kleijer et al., 2017; Wijayasundara et al., 2016). Therefore, recycling wastes as aggregates for lightweight concrete can contribute to both efficient waste management and the energy efficiency of buildings.

Polyisocyanurate (PIR), a type of polyurethane (PU) produced by combining methylene diisocyanate (MDI) with polyester polyol, is a material commonly used for thermal insulation. PIR foams are thermoset, closed-cell foams containing a low-conductivity blowing agent gas in their cells. The thermal resistance of PIR foams, as represented by the R-value, ranges from 2 to 2.5 m^2K/W; they are considered to be high-performance thermal insulation solutions. PIR foam is similar to rigid PU (PUR); they are both produced by combining MDI with a polyol. To produce PIR foam, polyester polyols are used, while PUR foam is produced using polyether polyols. Polyester is preferred for fire resistance application because of its higher glass-transition temperature (T_g) compared to polyether polyol. Apart from fire resistance, PUR/PIR also has high chemical and biological stability. It can resist the common chemical substances used in buildings such as solvents in adhesives, paints, or wood protection products as well as mold and decay. Ultraviolet radiation causes discoloration in PUR/PIR insulation boards, but this is not a technical drawback (European Union European regional development fund, 2007). In Asia Pacific (China, Japan, India, Australia, New Zealand, and Southeast Asia), PIR insulation had a market value of $0.66 billion and a volume of 457 KT in 2014, and it is expected to reach $1.06 billion and 704 KT in 2021. About 70% of the PIR in 2014 is used in the non-residential sector for commercial roof and side wall construction because the commercial and industrial building sectors demand higher performing material in terms of both

* Corresponding author.
E-mail address: tthanapol@tu.ac.th (T. Tantisattayakul).

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fire resistance and R-values (Frost and Sullivan, 2015a, 2015b). In Thailand, PIR foams have diverse applications, especially within the oil, gas, petrochemical, cryogenic, and refrigeration industries. It is used for pipe, vessel, and tank insulation. The estimated PUR/PIR consumption for panel and pipe insulation in the polyurethanes industry is expected to reach a volume of 4.4 KT in 2017 (The Federal of Thai Industries, 2018).

With the increasing use of global PIR insulation, the stability and volume of PIR foam waste (PIRW) streams from end-of-life and refurbishment projects will increase over the years. Efficient measures should be put in place to overcome the consequent environmental issues. In Europe, there are various end-of-life options for PU foam insulation with various pros and cons, and the optimum waste management consists of a good mix of recycling, recovery, and high efficiency waste-to-energy options (PU Europe, 2013). Most of the PU foam waste (200,000 t/yr) in the European Union (EU) is re-used for energy recovery in municipal solid waste combustors, and about 1000 t/yr of waste is used in powder form in other applications such as lightweight mortar (ISOPA, 2005). In America, the U.S. Environmental Protection Agency has suggested, based on the best environmental practices available, to ship PU foam insulation to nearby waste-to-energy incinerators instead of landfills for complete and safe destruction (United States Environmental Protection Agency, 2018). In China, the ministry of environmental protection has also supported professional disposal firms in recovering energy from the gases generated by the incineration of PU foam waste (Xiao et al., 2015). In Thailand, the appropriate options for managing PUR waste (PURW) were assessed by analyzing the impacts on the environmental, energy, and economic aspects. The results showed that recycling PUR waste as an aggregate in the production of lightweight concrete (LWC) is an appropriate management option without any financial subsidy required (Tantisattayakul et al., 2018). In Thailand, PIR foam waste (PIRW) is generated at a rate of approximately 450 t/yr or 11,250–15,000 m^3/yr; it is mostly generated during the PIR foam production, installation, and refurbishment processes and as a result of the replacement of PIR insulation during preventive maintenance in the oil, gas, and petrochemical industries (The Federal of Thai Industries, 2018). This PIRW is currently disposed of by incineration or in a landfill which requires a lot of space due to the low density of PIRW. Due to the acceptable mechanical and chemical properties of PIR material, the substitution of PIRW as a lightweight aggregate for the production of non-loadbearing concrete masonry units called lightweight concrete blocks (LWCBs) is of great interest (Haque et al., 2004; Junco et al., 2012; ASTM International, 2017).

LWCBs can usually be produced from Portland cement, water, and sand or lightweight aggregates and are intended for use in concrete masonry units when a prime consideration is the reduction of the density of the units. Three general types of lightweight aggregates are used: aggregates prepared by expanding, palletizing, or sintering products; aggregates prepared by processing natural materials; and aggregates consisting of the end products of coal or coke combustion. The aggregates are composed predominately of lightweight cellular and granular inorganic material (ASTM International, 2014a, 2017). PU is a lightweight material that is potentially much more flexible and hydrophobic than other traditional lightweight materials, such as perlite, expanded glass, or hollow micro-spheres, which may be useful for controlling the subsequent water absorption rates (Junco et al., 2012). The powder from PURW can be used in combination with cement as thermal insulating mortar for the levelling of floors and downward gradient of roofs. The specific advantages of this product are that it is lightweight, provides thermal and acoustic insulation, and is easy to handle (ISOPA, 2001; Archello, 2018).

Many studies have reported on the mechanical recycling of PURW to form a low-density aggregate which is used in LWCB (Yang et al., 2012), but specific references relative to the recycling of PIRW are scarce. Fraj et al. (2010) investigated this valorization of PURW, mixing 34–45 vol.% PURW aggregate with cement, sand, water, and superplasticizer to form LWCB samples with air-dried densities of 1500–1800 kg/m^3. Gadea et al. (2010) studied the use of PURW in cement-based mixtures to produce lightweight mortar. The dosages were varied, with 0–100 vol.% of the sand being replaced with PURW. The fresh densities of the lightweight mortar samples were 1100–2000 kg/m^3. Mounanga et al. (2008) prepared and characterized LWCB samples produced by mixing 13.1–33.7 vol.% PURW with cement, water, sand, and limestone; the fresh densities of the resulting LWC-PURW samples were 1100–1600 kg/m^3. However, when comparing these densities to those of commercial LWCBs (600–1000 kg/m^3), it was found that they were much higher, making product marketing difficult. Recently, most commercial LWC in Thailand is cellular lightweight concrete (CLC), which is a cement paste or mortar that

Table 1
General acceptance criteria for CLC mixtures according to the TIS standard (Thai Industrial Standards Institute, 2013).

Class of LWC*	Density (kg/m^3)	Compressive strength (MPa)	Water absorption (% by mass)
C8	701–800	> 2	< 25
C9	801–900	> 2.5	< 23
C10	901–1000		

Note: *The LWC classes are defined by a range of density.

Table 2
Typical chemical composition and physical properties of ordinary Portland cement Type I.

Composition (%)	
Silicon dioxide (SiO_2)	20.9
Aluminum oxide (Al_2O_3)	5.6
Ferric oxide (Fe_2O_3)	3.1
Calcium oxide (CaO)	62.7
Magnesium oxide (MgO)	2.2
Sodium oxide (Na_2O)	0.2
Potassium oxide (K_2O)	0.8
Sulfur trioxide (SO_3)	2.9
Property	
Loss on Ignition (%)	1.3
Specific Gravity	3.15
Blaine Fineness, cm^2/g	3,500

Table 3
Physical properties of the PIR foam.

Property	Unit	Value	Test standard
Blowing agent		HCFC141b	
Density	kg/m^3	32–80	ASTM D1622
Compressive strength	MPa	0.12–0.28	ASTM D1621
Thermal conductivity	W/m K	0.02	ASTM C518
Closed cell content	%	92	ASTM D2856
Water absorption	% v/v	2	ASTM D2842
Service temperature	°C	−180 to 90	

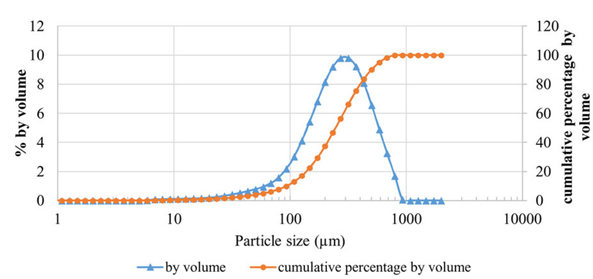

Fig. 1. Particle size distribution of PIRW crushed by granulator.